MENU COSTS AND MARKOV INFLATION: A THEORETICAL REVISION WITH NEW EVIDENCE

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Menu Costs and Markov Inflation: A Theoretical Revision with New Evidence

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Abstract

We revisit a foundational theoretical paper in the menu cost literature, Sheshinski and Weiss (1983), one of the few to treat stochastic inflation with persistent deviations from trend. In contrast to the original finding, we find that optimal pricing in this environment entails using different (s, S) bands in high-inflation and low-inflation states of the world. The low-inflation band is strictly contained within the high-inflation band. This revised solution has very different implications from the original one. Firms are generally risk-loving, not risk-averse, with respect to inflation. An increase in the variance of inflation increases price dispersion when inflation is high and decreases price dispersion when inflation is low. On an aggregate level, this optimal pricing would lead to bunching of prices and non-neutrality of money in the setting of Caplin and Spulber (1987). To test the main finding, we construct an establishment-level dataset from the months surrounding Mexico's "Tequila crisis" in 1995. In the high-inflation state, price increases are larger and establishments allow their prices to vary more widely around their respective long-run mean relative prices. Cross-establishment price dispersion is lower, but this result seems due to decreased establishment heterogeneity rather than narrower (s, S) bands. Overall, the evidence suggests that establishments employ wider (s, S) bands in the high-inflation state.

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1 Introduction

Price stickiness at the firm level and its implications for aggregate behavior have been analyzed extensively. Studies have examined the relationship between money growth, inflation, and output by assuming an economy of firms following (s, S) pricing policies. Caplin and Spulber (1987) find monetary neutrality in a simple (s, S) economy, while Caplin and Leahy (1991, 1997) find that money can affect output or prices, depending on recent history. Dotsey et al. (1999) and Danziger (1999) introduce shocks to firms' menu costs and firms' productivity, respectively, to facilitate general equilibrium monetary analysis with endogenous price inflexibility. Golosov and Lucas (2005) incorporate firm productivity shocks along with menu costs in a model that matches high- and low-inflation micro-data well, and find negligible real effects of money.

Underpinning much of this literature is a micro literature, pioneered by Sheshinski and Weiss. It establishes the optimality at the firm level of an (s, S) policy, under which a firm allows its relative price to drift below its optimal price, to s, and then adjusts it above its optimal price, to S. This type of policy is optimal for a firm facing a constant rate of inflation and a fixed cost of adjusting price, as shown by Sheshinski and Weiss (1977, hereafter SW77).

The same authors have shown the (s, S) policy optimal when inflation is stochastic in the sense that the economy alternates between two regimes, one with positive inflation and the other with no inflation, according to two stochastic duration times (1983, hereafter SW83). Further, the (s, S) band was found to be identical to the one the firm would choose if facing a deterministic rate of inflation *higher* than the average inflation rate of the stochastic process. In other words, there was found to be a risk-premium associated with inflation. Finally, it was found that an inflation process with a higher variance gives rise to a wider (s, S) band.

In this paper we re-solve the model and find that a single (s, S) policy cannot be optimal under these circumstances of stochastic inflation.[1] Rather, there will be two different (s, S)

[1] An addendum to a reprint of SW83 in Sheshinski and Weiss (1993, p. 167) acknowledges an error might exist, since the option of changing price upon switching to state 0 was not taken into account. It conjectures that there are two different (s, S) bands corresponding to the two inflation rates, the zero-inflation one

bands, corresponding to the two different inflation regimes, with the zero-inflation band strictly contained within the positive-inflation band. When inflation stops, some firms may find it optimal to raise their prices immediately rather than to wait for inflation to start again and for the price to drift down further. There may also be downward adjustments in price by firms who find themselves with a price at the high end of the positive-inflation (s, S) band when inflation stops.

Given that firms will employ two different (s, S) bands, no equivalence can hold between the stochastic case and the deterministic case (which involves a single (s, S) band). This equivalence was key to the other findings of SW83; hence we assess whether these other findings continue to hold.

The original finding that higher variance of inflation leads to wider (s, S) bands gives way to a more nuanced picture. Here, higher variance leads to wider (s, S) bands in the high-inflation state of the world, but more narrow (s, S) bands in the zero-inflation state of the world. In a sense, it increases the elasticity of the (s, S) parameters to the current inflation rate.

We also find that there is no risk-premium associated with inflation in general. Surprisingly, firms often prefer a stochastic inflation process to a deterministic one with the same average drift in prices. This is even true when the stochastic inflation process is set to start in the high-inflation state. We conjecture this is due to the firm's inflation-related cost being convex in the rate of inflation. Roughly speaking, if the inflation rate doubles, the firm can do no worse than bear double the menu costs by keeping the same (s, S) band; but it may do better.

The dual-(s, S) band solution has a number of other implications. For example, Caplin and Spulber (1987) show that money is neutral if firms are distributed uniformly and follow *single* (s, S) bands in pricing. However, if firms price optimally and money growth is as modeled here, money can no longer be neutral. Consider a regime switch from zero to

narrower than the other.

positive money growth. The (s, S) bands immediately widen and some time will elapse before any firm's normalized price drifts down to the new, lower trigger point s. That is, prices will not change instantaneously, and for some time, money will have real effects. Conversely, consider a regime switch from positive to zero money growth. The (s, S) bands narrow and a mass of firms immediately change prices upward,[2] leading to negative real effects. In this sense, the model would predict inflationary inertia and output costs when a disinflation is enacted. In general, state-dependent (s, S) bands lead to bunching of firms, making a uniform distribution impossible to maintain and leading to real effects of money.

A key implication of the model is that (s, S) bands are themselves state-dependent: they vary with inflationary expectations and, under inflationary persistence, are wider during a high-inflation regime.[3] We test this by constructing a new establishment-level dataset from before and after Mexico's "Tequila crisis" in 1995. This event saw persistently low rates of inflation give way nearly overnight to high rates. It thus appears to be a good match for the model. The data are monthly prices of 44 goods, over 22 months, each good from 10-22 different establishments in Mexico City.

The data reveal increases in both frequencies and magnitudes of price adjustments after the crisis. The result that price increases are larger provides direct evidence that (s, S) bands widened with the rise in inflation. We also construct measures of price dispersion that aggregate deviations from firms' *own* long-run average prices rather than deviations from *other firms'* average prices. We use these in panel regression tests that are robust to firm heterogeneity and price change synchronization. As the model predicts, these deviations tend to be larger in the high-inflation state.

An alternative specification, similar to ones used in previous literature, involves regressing measures of cross-establishment price dispersion on inflation in a good fixed effects model. Results from these regressions support a seemingly opposite result: cross-establishment price dispersion is lower in the high-inflation state. However, the model's predictions for this

[2] The same kind of logic is found in Tsiddon (1991).

[3] This is also a prediction of the Dotsey et al. (1999) calibrated model.

kind of price dispersion rely on homogeneity and asynchronous price changes across firms. Our theory and data do not support these assumptions. For example, there are persistent differences in pricing across establishments for reasons unrelated to menu costs. We find evidence that this cross-establishment heterogeneity in pricing declined after the crisis, which partly explains how cross-establishment price dispersion declined even though (s, S) bands widened. Overall, the evidence suggests that the menu-cost component of price dispersion did increase with inflation.

It is important to note that we are not testing state-dependent pricing against time-dependent pricing, a focus of much of the recent literature. A common approach (see Klenow and Kryvtsov, 2005) is to decompose inflation changes into changes in frequencies and magnitudes of price changes, associating the former with state-dependent pricing and the latter with time-dependent pricing. Indeed, our key findings, larger price changes and intrafirm price variability due to higher inflation, are also predicted by time-dependent pricing models. However, one key point of this paper is to emphasize that state-dependent, and not just time-dependent, models predict that price change magnitudes respond to changes in inflation and inflation expectations. Further, our data do show both magnitudes and frequencies of price adjustment responding significantly to inflation.

The paper is organized as follows. Section 2 describes the model. Sections 3.1 and 3.2 derive the key analytical results of the paper, namely that the optimal policy involves different (s, S) bands in each state, with the low-inflation band strictly contained in the high-inflation band. The core of the paper is section 3.3, which discusses the implications of this revised solution. Section 4 discusses computation and presents the effects of more variable inflation on the (s, S) bands and the effects of inflation uncertainty on firm value. Section 5 describes the data and provides some empirical evidence. Section 6 concludes.

2 The Model

Following SW83, we assume that there are two states of the world, or inflationary 'regimes', $i = 0$ and $i = 1$. In state i, the aggregate price level is increasing at constant rate ig. Thus in state 0 a firm's log relative price, p, is constant. In state 1, it decreases linearly with time: $p_{t+\delta} = p_t - g\delta$. The world alternates between the two states stochastically. The length of any sojourn in state 1 (state 0) is distributed exponentially with parameter $\lambda_1 > 0$ ($\lambda_0 > 0$).[4]

The firm's profit per unit of time as a function of the firm's log relative price is $\Pi(p)$. $\Pi(p)$ is assumed to be continuously differentiable, strictly concave, and maximized at p^*. Profits are discounted at rate $r > 0$.

The firm is assumed to observe the aggregate price level and inflation rate instantaneously. Thus it can condition its policy on its own relative price and the inflation regime. To change its nominal price, the firm must pay a fixed menu cost of $B > 0$.

The firm maximizes expected profits net of menu costs. It does so by choosing the amount to adjust its price (including zero) at all dates and histories, inflationary regimes, and own relative prices. Note that the exponential distribution implies constant exit rates from each regime. The inflation process thus has the Markov property. Hence, expectations over future inflation are invariant to the amount of time elapsed in the current state and past inflationary history. The only relevant data for the firm's decision are its own relative price and the inflationary state of the world.[5]

Thus the firm can be said to maximize profits by choice of two functions: $\kappa(p, i)$, which equals zero if no price change takes place at relative price p in state i and one otherwise, and $\hat{p}(i)$, which gives the target price for each state when a price change occurs.[6] Define τ^∞ as an infinite, ordered sequence of non-negative real numbers, $\{\tau_1, \tau_2, ...\}$ with $\tau_j < \tau_{j+1}$. Every potential inflationary history is such a sequence where the τ_j's are interpreted as

[4]SW83 assume only that the hazard rate for state 0 is non-increasing with time. Our assumption of a constant hazard rate λ_0 is stronger, but included in theirs.

[5]This history independence of the firm's decision is the reason we strengthen SW83's assumption by imposing a Markov structure, i.e. a constant hazard rate in state 0.

[6]The target price will not depend on the current price since the firm can change to any price at cost B.

times that the regime changes. Similarly, define T^∞ as an infinite ordered sequence of real numbers, $\{T_1, T_2, ...\}$ with $T_j < T_{j+1}$. The T_j's represent times at which the firm changes its price.[7] Given a sequence of regime switching times τ^∞, initial relative price p_0 and state i_0, and functions $\kappa(p,i)$ and $\hat{p}(i)$, both T^∞ and p_t, the time path of the firm's price, are fully determined. Leaving this dependence implicit, one can write the value of a firm with current relative price p_0 in state i_0 as

$$V(p_0, i_0) = \max_{\kappa(p,i),\ \hat{p}(i)} \quad E_{\tau^\infty}\left[\int_0^\infty e^{-rt}\Pi(p_t)dt - B\sum_{j=1}^{\infty} e^{-rT_j}\right]. \tag{1}$$

Henceforth[8] we let $V_i(p) \equiv V(p,i)$ and $S_i \equiv \hat{p}(i)$, for $i = 0, 1$. Also, we let $A_i \equiv \{p : \kappa(p,i) = 1\}$ and $I_i = \Re \setminus A_i$. Thus A_i is the action region for state i, and I_i the inaction region. It is clear that for $p \in A_i$,

$$V_i(p) = V_i(S_i) - B, \tag{2}$$

for $i = 0, 1$. For concreteness, we assume an indifferent firm changes price.

Note that I_1 must contain a convex subset of positive measure; otherwise, infinite costs would be incurred. Let $[s, p]$ be such a subset. Then

$$\begin{aligned} V_1(p) = &\int_0^{\frac{p-s}{g}} \lambda_1 e^{-\lambda_1 \tau}\left[\int_0^\tau e^{-rz}\Pi(p-gz)dz + e^{-r\tau}V_0(p-g\tau)\right]d\tau + \\ &\int_{\frac{p-s}{g}}^\infty \lambda_1 e^{-\lambda_1\tau}\left[\int_0^{\frac{p-s}{g}} e^{-rz}\Pi(p-gz)dz + e^{\frac{-r(p-s)}{g}}V_1(s)\right]d\tau. \end{aligned} \tag{3}$$

The first line represents the case where the regime switches at time τ before the price drifts down from p to s, in which case the termination value is $V_0(p-g\tau)$. The second line represents the case where the regime does not switch and the termination value can be thought to be

[7]Price changes must occur at discrete intervals if the firm is to avoid incurring infinite costs.

[8]Here the expectation of some function $Q(\tau^\infty)$ can be written as

$$E_{\tau^\infty}[Q(\tau^\infty)] = \int_0^\infty \int_{\tau_1}^\infty \int_{\tau_2}^\infty \cdots \quad Q(\tau^\infty)\ \ldots e^{-\lambda_1(\tau_3-\tau_2)}e^{-\lambda_0(\tau_2-\tau_1)}e^{-\lambda_1\tau_1}\ \ldots d\tau_3 d\tau_2 d\tau_1$$

when $i_0 = 1$. When $i_0 = 0$, the λ_1's and λ_0's are switched.

$V_1(s)$. Changing variables to prices rather than time, carrying out an integration by parts, and defining $R_i \equiv r + \lambda_i$, for $i = 0, 1$, gives

$$V_1(p) = e^{\frac{-R_1(p-s)}{g}} V_1(s) + \int_s^p e^{\frac{-R_1(p-z)}{g}} \left[\frac{\Pi(z) + \lambda_1 V_0(z)}{g} \right] dz. \tag{4}$$

Taking the derivative, whose existence is addressed in lemma 1 below, gives

$$R_1 V_1(p) = \Pi(p) + \lambda_1 V_0(p) - g V_1'(p) \tag{5}$$

for p in the interior of I_1.

A similar approach can be taken with state 0. The expression analogous to equation 3 is simpler since there is no drift in price. For any $p \in I_0$,

$$V_0(p) = \int_0^\infty \lambda_0 e^{-\lambda_0 \tau} \left[\int_0^\tau e^{-rz} \Pi(p) dz + e^{-r\tau} V_1(p) \right] d\tau = \frac{\Pi(p) + \lambda_0 V_1(p)}{R_0}.$$

Rearranging gives

$$R_0 V_0(p) = \Pi(p) + \lambda_0 V_1(p). \tag{6}$$

3 The State-Dependent Solution

3.1 Preliminary Results

As a preliminary step, we show continuity and differentiability of both state's value functions.

Lemma 1. *The value functions $V_0(p)$ and $V_1(p)$ are continuous. Both state's inaction regions consist of one or more disjoint, open intervals. $V_1(p)$ is differentiable everywhere except (potentially) at boundary points of A_1. $V_0(p)$ is differentiable everywhere except (potentially) at boundary points of A_0 and A_1.*

Proof. See Appendix A.

Continuity comes essentially from the value functions being the maximum of two continuous functions, corresponding to the values of inaction and action. Differentiability in state 1 comes from continuity, interestingly, of the profit function and the state-0 value function. Differentiability in state 0 comes from differentiability of the profit function and of the value function in state 1. Next we establish differentiability on any lower boundary of I_1, that is, the familiar smooth pasting condition.

Lemma 2. *(Smooth Pasting) If at price s there exists an $\epsilon > 0$ such that $(s, s+\epsilon) \subset I_1$ and $(s-\epsilon, s) \subset A_1$, then $V_1'(s) = 0$.*

Proof. Note that equation 4 with $p = s+\epsilon/2$ applies. Optimality implies that varying the inaction region boundary s either up or down should not improve firm value at p. Consider such a temporary variation, that is, increasing s marginally but reverting back to the original s after either the regime changes or a price change is made. The resulting change in value is, using equation 4,[9]

$$\frac{\partial V_1(p)}{\partial s} = 0 = e^{\frac{-R_1(p-s)}{g}} \left[\frac{R_1 V_1(s) - \Pi(s) - \lambda_1 V_0(s)}{g} \right]. \tag{7}$$

Combining this with equation 5 gives that $\lim_{p \downarrow s} V_1'(p) = 0$. We also know from equation 2 that $\lim_{p \uparrow s} V_1'(p) = 0$. ■

We next show that the optimal policy is indeed of the (s, S) form, though perhaps a different one for each state. Equivalently, we show each inaction region is convex, consisting of a single interval. This follows from the concavity of the profit function.

Lemma 3. *For $i = 0, 1$, inaction region I_i equals (s_i, N_i), with $s_i < p^* < N_i$.*

Proof. See Appendix A.

The proof starts from the fact that each inaction region is a collection of disjoint, open intervals. It then takes an arbitrary one for each state and uses the shape of the profit

[9] The change in s does not affect $V_0(z)$ in equation 4 since it is ignored after a regime switch. It does not affect $V_1(s)$, since this equals $V_1(S_1) - B$, which is unchanged since the change in s is ignored after a price change.

function to show that the interval's lower bound must be below p^* and its upper bound must be above p^*. This proves there is a single such interval for each state, with p^* contained.

Thus the optimal policies are indeed (s, S) policies, though possibly state-dependent. The value functions satisfy continuity and differentiability except at some boundary points, and smooth pasting holds at s_1. Next we examine how optimal pricing compares across inflationary regimes.

3.2 Relative location of parameters

The restrictions imposed by optimality, value matching, and smooth pasting are sufficient to establish almost completely the relative locations of (s_i, S_i, N_i), $i = 0, 1$. The relative location of S_1 and N_0 is the one fact that depends on parameter values.

In models with monotonic downward drift in prices, the upper boundary of the inaction region (N_i here) is typically irrelevant. This is because prices only move upward when changed to the target price S_i, less than N_i. Here, N_0 may figure into long-run behavior. Computation (see section 4) shows that sometimes $N_0 < S_1$. In this case, a downward price change occurs when state 1 gives way to state 0 and the price is in (N_0, S_1).

To illustrate, examples of relative price paths of a firm following an optimal policy are graphed in Figure 1. In state 1, the relative price drifts down with inflation, while in state 0 it remains flat. In the first example, $S_1 < N_0$. Since the price will be contained within $[s_1, S_1]$, there will be no downward price adjustments. The only adjustments possible are from s_1 to S_1 in state 1 (as occurs in the graph just before $t = 4$) and from anywhere in $(s_1, s_0]$ to S_0 in state 0 (as occurs just before $t = 10$). In the second example, $N_0 < S_1$, and there can be downward adjustments if the firm finds itself with a price too high when inflation stops (as occurs in the graph just after $t = 4$). All the price adjustments of the previous case are possible, in addition to adjustments from anywhere in $[N_0, S_1)$ to S_0 in

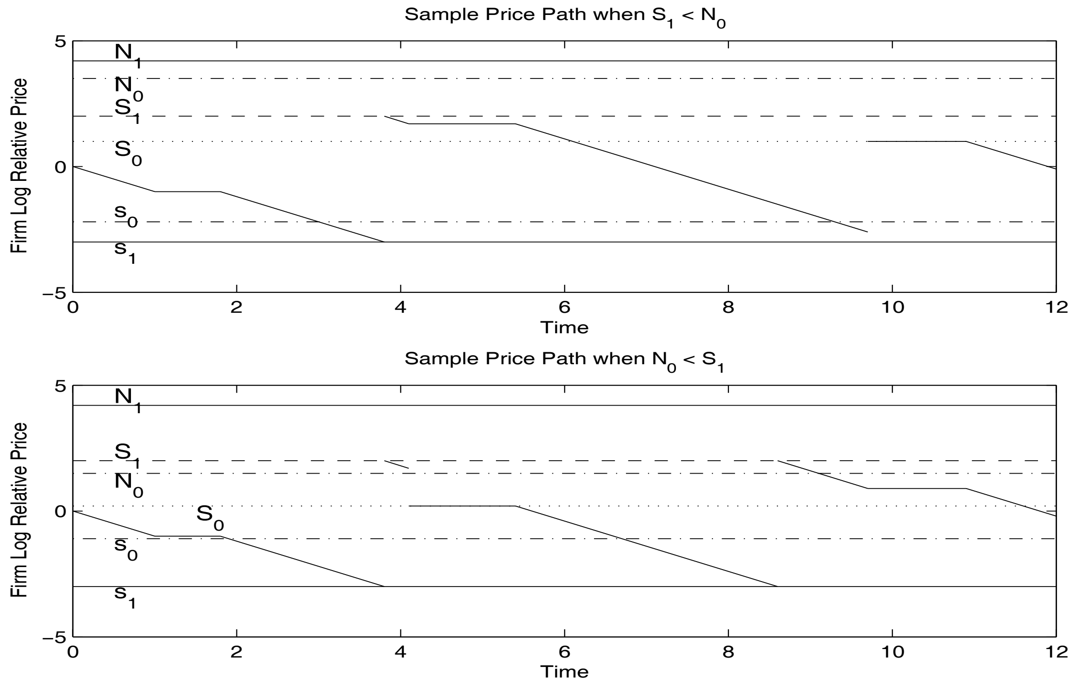

Figure 1: Sample price paths when $S_1 < N_0$ and when $N_0 < S_1$.

state 0. The following assumption is sufficient (not necessary) to guarantee that $S_1 < N_0$:

$$\frac{1}{\lambda_1} + \frac{1}{R_0} \leq \frac{B}{\Pi(p^*)}. \tag{A1}$$

Proposition 1. *The inaction region of state* 0 *is fully contained in the inaction region of state* 1*, and* $(s_0, S_0) \subset (s_1, S_1)$*. Specifically,* $s_1 < s_0 < p^* < S_0 < S_1, N_0 < N_1$*. Under the additional assumption A1 and supposing the firm has a (weakly) positive net present value in state* 1*,* $S_1 < N_0$*.*

Proof. By lemmas 4-7 below.

Lemma 4. *Each state has a unique target price* S_i*, with* $p^* < S_0 < S_1$*.*

Proof. See Appendix A.

The uniqueness of each state's optimal prices comes from the concavity of the profit function. The fact that $S_1 > p^*$ is due to the downward drift in prices, which makes it appealing to overshoot the optimal price. Finally, it is not surprising that $S_0 \in (p^*, S_1)$. This is clear from equation 6, which shows the tradeoff between current profits, which would push the choice toward p^*, and the value when inflation starts again, which would push the choice toward S_1.

Lemma 5. $s_1 < s_0$.

Proof. We show below that state-0 value attains a strictly higher maximum than state-1 value: $V_1(S_1) < V_0(S_0)$. Since changing price is always an option, we know that $V_0(s_1) \geq V_0(S_0) - B$. Note also that $V_1(s_1) = V_1(S_1) - B$. Combining these facts gives $V_0(s_1) > V_1(s_1)$. We show next that $s_1 \geq s_0$ implies $V_0(s_1) = V_1(s_1)$, a contradiction.

Assume $s_1 \geq s_0$. Then s_1 is on the boundary or in the interior of both states' inaction regions. Thus the inaction region value functions 5 and 6 apply at s_1. Solving them simultaneously and using smooth pasting gives that $V_0(s_1) = V_1(s_1)$.

Finally, we show $V_1(S_1) < V_0(S_0)$. Define $v_0(S_1)$ as the value in state 0 of remaining at price S_1 until the regime changes, and following the optimal policy thereafter. Of course, $V_0(S_1) \geq v_0(S_1)$. The same reasoning leading up to equation 6 gives that $R_1 v_0(S_1) = \Pi(S_1) + \lambda_0 V_1(S_1)$; thus

$$R_1 V_0(S_1) \geq \Pi(S_1) + \lambda_0 V_1(S_1).$$

Together with equation 5 and optimality condition $V_1'(S_1) = 0$, this implies $V_1(S_1) \leq V_0(S_1)$. Finally, $V_0(S_1) < V_0(S_0)$ since S_0 is the unique optimizer in state 0 (lemma 4). ■

Note that this holds for any parameter values λ_0, λ_1, and g. Thus there will always be a range of prices from which a firm will choose to switch when state 1 gives way to state 0.

Lemma 6. $N_0 < N_1$.

Proof. See Appendix A.

Thus the state-0 inaction region is fully contained within the state-1 inaction region: $(s_0, N_0) \subset (s_1, N_1)$. Of course, in the long run the firm's price is contained within (s_1, S_1), which strictly contains (s_0, S_0). It may contain even (s_0, N_0), in which case downward price changes may occur. Sufficient condition A1 rules this out.

Lemma 7. *Under assumption A1 and if the firm has a (weakly) positive net present value in state* 1, $S_1 < N_0$.

Proof. See Appendix A.

Condition A1 is intuitive. The left-hand side is roughly equivalent to the sum of expected durations in each state of the world, $1/\lambda_i$. The right-hand side is the menu cost relative to potential profit flows. Thus as long as the inflationary states are transitory enough, relative to the normalized menu cost, there will be no downward price changes. Highly transitory regimes make the two (s, S) bands similar, as firm pricing policy is based more on the average drift in prices rather than the current drift.

3.3 Discussion

The fact that the (s, S) bands vary with the inflationary state of the world has potentially significant implications. Most directly, there is no simple correspondence between the firm's behavior under this stochastic inflation process and under a simpler deterministic inflation process. This contrasts with the finding in SW83. Since the comparative statics of SW83 are based on this finding, the questions addressed there are re-opened. In particular, how does more variable inflation affect firm pricing? We address this in section 4.

A second direct implication of the solution here is that forward-looking firms do indeed allow their prices to vary more widely in a high-inflation environment (with persistence). This implication was plausible after SW77, which established that a firm facing a higher *deterministic* rate of inflation would allow its price to vary more widely. To take SW77 to time series data, however, would involve assuming that firms are always surprised by a change in the inflation rate and believe the current one will last forever. SW83 moved in a crucial direction by introducing a stochastic inflationary process, for which firms fully account in their pricing. Taking this model to the data could thus be done with greater confidence. However, the implication of a wider band in a high-inflationary period was lost: firms were found to use the same (s, S) band whether inflation was high or low. The solution here resolves this tension and restores the implication of wider dispersion under higher inflation to solid theoretical footing. We test it in section 5.

Related to this, under the original solution of SW83, higher inflation (i.e. a regime change) results in greater frequencies of price adjustment but no change in magnitudes of price adjustment, due to the single (s, S) band. An association of state-dependent pricing with frequencies of adjustment as the key margin, and time-dependent pricing with magnitudes of adjustment as the key margin, (as in Klenow and Kryvtsov, 2005) would thus be well-founded. However, as our solution here shows, state-dependent pricing does indeed predict a positive correlation between inflation and magnitudes of price adjustment, since the (s, S) bands widen with inflation. On the other hand, the correlation between inflation and frequencies of price adjustment is not entirely clear here and may well be negative: prices fall faster but have further to fall. In fact, in the related non-stochastic case of SW77, restrictions on the profit function were necessary to ensure that the frequency of price adjustment increased with inflation; they produce an example in which inflation rises but frequency of price adjustment falls due to (s, S) band widening. These results and ours suggest it is not a general conclusion that changes in frequencies of price adjustment predominate under state-dependent pricing.[10]

The solution here also adds some complexity to the empirical implications of (s, S) pricing. For example, Eden (2001) summarizes, tests, and rejects three implications of (s, S) pricing, two of which hold under the solution of SW83 but none of which hold here. The first implication cited is that the magnitude of price changes should equal the amount the

[10] On the other hand, Klenow and Krytsov (2005) do show that frequencies of adjustment are predominant in the state-dependent pricing model of Dotsey et al. (1999) as originally calibrated. This may be due, however, partly to the specific parametrization of the profit function and the distribution of menu costs. Other state-dependent models show different results. For example, Golosov and Lucas (2005) find a high importance of magnitudes of price adjustment in their state-dependent model; however, in their case it may be driven primarily by the idiosyncratic firm shocks rather than the (s, S) band changes we stress here.

real price has eroded since the last price change. This is true if firms always adjust to the same S, but not if their target prices vary by state, as they do here ($S_0 < S_1$). The second is that price jumps are equal across time in one-sided (s, S) settings. In the solution here, the size of the price jump increases with the current rate of inflation. The third is that the level of the real price after a change does not depend on whether the price was raised or lowered. Here, a downward change can only happen when inflation is low (i.e. 0) and thus the target price (S_0) is low, while upward price changes can occur under either rate of inflation and thus the target price may be high or low (S_0 or S_1). Indeed, Eden (2001) finds that downward changes result in lower real prices than upward changes.

There are implications for macroeconomic models as well. These can best be understood in the setting of Caplin and Spulber (1987), who consider a continuous money growth process in continuous time, as we do.[11] If money growth follows the stochastic process assumed here and firms follow the optimal, regime-dependent (s, S) policies, then money will not be neutral. To see this, consider starting in the zero-money-growth regime. When the regime gives way to the positive-money-growth regime, the (s, S) bands will immediately widen. There will be an interval of time with no price changes, long enough for the lowest normalized price to drift down from s_0 (or above it) to s_1. Thus at the beginning of inflationary periods, all money growth would translate into real effects.[12]

Consider now a disinflation in which money growth is halted. The (s, S) bands shrink and a mass of firms now find themselves outside the inaction region (between s_1 and s_0) and change prices upwards.[13] That is, there would be a burst of inflation in response to the slower money growth, and a concomitant real contraction.[14] This case holds when $S_1 \leq N_0$, in which

[11]It is the money supply that evolves stochastically in Caplin and Spulber (1987), as compared with the aggregate price level here.

[12]Of course, monetary neutrality does hold if firms use a single (s, S) band, which is the case considered by Caplin and Spulber (1987).

[13]The intuition here is similar to that of Tsiddon (1991). Almeida and Bonomo (2002) also discuss the effect of a shrinking (s, S) band after a disinflation.

[14]In Burstein's (forthcoming) framework, the sticky price model does not produce inertial inflation and negative real effects, while the sticky plan model – in which firms can pay a menu cost to choose *all* future prices – does. Of course, the conjecture we outline here would have an instantaneous, not protracted, burst of inflation; this is in contrast with his sticky plan model.

case there would be no price decreases. However, if the reverse condition holds, then there will be some price decreases (from firms between N_0 and S_1) as well as price increases. The decreases could mitigate or even cancel the inflationary burst and the negative real effects. The case with counterbalancing price decreases is more likely the greater is the disinflation (g) and the more credible it is (λ_0 near zero), since these accentuate the differences in the (s, S) bands and make $N_0 < S_1$ more likely to hold. This is in line with the view that large and credible disinflations may be less costly than small ones.

More generally, the solution in this paper gives rise to endogenous bunching of firms. In fact, if firms are identical (except in initial prices), it appears to give rise to a degenerate distribution of prices in the long run. This conjecture is based on the following reasoning. First, when two firms reach the same price, they stay at the same price forever. Second, all firms that end up in $(s_1, s_0]$ when inflation stops change to the same price, S_0. Thus the distribution will 'eventually' be a finite number of spikes. Third, any two spikes will 'eventually' be in $(s_1, s_0]$ together when inflation stops.[15] Only one spike remains in the end.

Of course if s_0 is close to s_1, the degeneracy will be a long time in coming. Further, the degeneracy would not survive the kind of randomization introduced in Caplin and Leahy (1991). On the other hand, it is clear that a uniform distribution of firms will not last even with such randomization. The fact remains that there is a force for bunching of firms in the solution proposed here.[16] Bunching in turn will cause money to have real effects at times, though presumably not in an easily tracked pattern.

The solution proposed here also suggests a key (conjectural) condition for a single (s, S) band to be inadequate: persistence in the stochastic element of inflation (or of the money supply). If the future of inflation always looks the same regardless of present or past inflation,

[15]This might not be true if any two spikes remained at the same distance from each other indefinitely. But there is random variation in the distance between any two spikes due to state-0 price changes.

[16]Bunching here does not seem to be an artifact of the *discontinuous* changes in inflationary expectations, which give rise to discontinuous changes in (s, S) bands. It is hard to imagine a uniform distribution being preserved even if the bands change continuously over time. This would require that as the width of the band shrank, say, firms would be re-distributed evenly over the whole remaining band; but in general, they will be switching to an area near the top of the band.

a firm need never change its (s, S) band. This holds true if inflation is constant or if prices follow a random walk or Brownian motion, with or without drift. These are the cases most common in the literature. On the other hand, if the inflationary future looks different depending on current or past inflation, (s, S) bands will themselves be state-dependent. In the SW83 model there are exactly two inflationary outlooks, with the current rate of inflation summarizing all helpful information. This gives rise to two (s, S) bands. More general models may be much more complicated. But whether a single (s, S) band is a good approximation seems to hinge on the persistence of inflation, an issue which can be addressed empirically.[17]

We note finally that consistent aggregation does not result from the solution here. That is, the sum of firms' pricing decisions does not replicate the inflation process to which they are responding.[18] Aggregation is possible if a single (s, S) band is used, as Caplin and Spulber (1987) have pointed out. However, assume firms use the optimal, regime-dependent (s, S) bands. As inflation stops, there is a burst of upward price changes: all firms that find themselves in $(s_1, s_0]$ change upward to S_0. This would mean that inflation jolted forward also, a contradiction to its having stopped. Conversely, any time inflation restarted, all firms would initially have prices higher than s_0; there would thus be no price changes for some interval of time as the lowest prices drifted from above s_0 down to s_1, a contradiction to inflation's having restarted.

4 Computation

Here we derive a system of equations and conditions that allow computation of the key parameters. The results of section 3 allow us to express the value functions in terms of a

[17]Estrella and Fuhrer (2002), among others, show that the impulse response of U.S. inflation to nominal and real shocks exhibits persistence. Some argue that inflation persistence is not inherent in an economy but varies significantly with the credibility and policies of the monetary authority. See the discussion and references in Erceg and Levin (2003), for example.

[18]Recall that firm profits in this paper depend on the firm's price relative to the aggregate price level. If instead profits depended on the firm's price relative to the money supply, as in Caplin and Leahy (1991), this aggregation question would not be an issue.

boundary and the profit function only. In particular, proposition 1 establishes that (s_0, N_0) is a subset of both states' inaction regions. Thus equations 5 and 6 both apply on this interval. Solving them simultaneously gives

$$rV_1(p) = \Pi(p) - g_1 V_1'(p) \tag{8}$$

and

$$rV_0(p) = \Pi(p) - g_0 V_1'(p) = \Pi(p) + (g_1/R_0)\Pi'(p) - g_1 V_0'(p), \tag{9}$$

where $g_1 \equiv g(r + \lambda_0)/(r + \lambda_0 + \lambda_1)$ and $g_0 \equiv g\lambda_0/(r + \lambda_0 + \lambda_1)$.

These equations allow for interesting non-stochastic interpretations of the value functions. Equation 8 is exactly the value function for a firm facing a constant rate of inflation g_1 forever. Note that g_1 is higher than the asymptotic average rate of inflation, $\overline{g} \equiv g\lambda_0/(\lambda_0+\lambda_1)$. This is not due to induced risk aversion,[19] but since it applies to a firm *starting* in the high-inflation state. This interpretation is corroborated in the fact that g_1 is the expected discounted inflation rate conditional on starting in state 1, and similarly for g_0 in state 0.[20]

Differential equations 8 and 9 have the following solutions, valid over the common inaction region and its boundaries, $[s_0, N_0]$:

$$V_1(p) = e^{\frac{-r(p-s_0)}{g_1}} V_1(s_0) + \int_{s_0}^{p} e^{\frac{-r(p-z)}{g_1}} \frac{\Pi(z)}{g_1} dz, \tag{10}$$

and

$$V_0(p) = e^{\frac{-r(p-s_0)}{g_1}} V_0(s_0) + \int_{s_0}^{p} e^{\frac{-r(p-z)}{g_1}} \left[\frac{\Pi(z)}{g_1} + \frac{\Pi'(z)}{R_0}\right] dz. \tag{11}$$

State-1 value over $(s_1, s_0]$ and $[N_0, N_1)$ looks different. For every p in these intervals,

[19] The solution of SW83 can be derived from imposing optimality, value matching, and smooth pasting on equation 8. In that solution g_1 has a natural interpretation as the certainty equivalence rate of inflation, and it appears that uncertainty widens the (s, S) band of the firm. But different parameter values would be found if the same conditions were applied to equation 9 rather than 8. That is, a different (s, S) band would be derived if value conditional on starting in state 0, rather than in state 1, were maximized.

[20] Specifically, $g_1 = E[\int_0^\infty re^{-rt}\pi(t)dt|\, i_0 = 1]$ and $g_0 = E[\int_0^\infty re^{-rt}\pi(t)dt|\, i_0 = 0]$, where $\pi(t) = gi(t)$ is the rate of inflation.

$V_0(p) = V_0(s_1)$, since s_1 and these prices are all in the state-0 action region. Using this fact, smooth pasting, and equation 5, we can write the following differential equation:

$$R_1[V_1(p) - V_1(s_1)] = \Pi(p) - \Pi(s_1) - gV_1'(p),$$

which applies over $(s_1, s_0]$ and $[N_0, N_1)$. The solution over $(s_1, s_0]$ is

$$V_1(p) = V_1(s_1) + \int_{s_1}^{p} e^{\frac{-R_1(p-z)}{g}} \frac{\Pi(z) - \Pi(s_1)}{g} dz \tag{12}$$

and over $[N_0, N_1)$ is, since $V_1(s_1) = V_1(N_1)$,

$$V_1(p) = V_1(N_1) - \int_{p}^{N_1} e^{\frac{-R_1(p-z)}{g}} \frac{\Pi(z) - \Pi(s_1)}{g} dz. \tag{13}$$

Equations 10-13 completely describe the value functions for both states in their respective inaction regions. The value in action regions is given by equation 2. Given a profit function, we can solve for the six parameters $(s_0, s_1, S_0, S_1, N_0, N_1)$ and boundary value $V_1(s_0)$ (from which $V_0(s_0)$ is known given equation 6). This is done using seven conditions imposed on the equations above and others: $V_i'(S_i) = 0$, $i = 0, 1$; $V_1'(s_1) = 0$; $V_i(S_i) = V_i(s_i) + B$, $i = 0, 1$; and $V_i(S_i) = V_i(N_i) + B$, $i = 0, 1$.

4.1 Effect of Inflation Variability on Pricing

Figure 2 shows what happens to (s_i, S_i, N_i), $i = 0, 1$, as the λ_i's decrease. Note that a decrease in the λ_i's prolongs the expected stay in each state. It also represents a mean-preserving increase in the variance of inflation, as long as the ratio λ_1/λ_0 is held constant, as SW83 show.

In the original solution, the result was that higher variance of inflation widened the single (s, S) band (since this increases g_1). Here, the result is state-dependent: a mean-preserving increase in inflation variability tightens the low-inflation state bands and widens

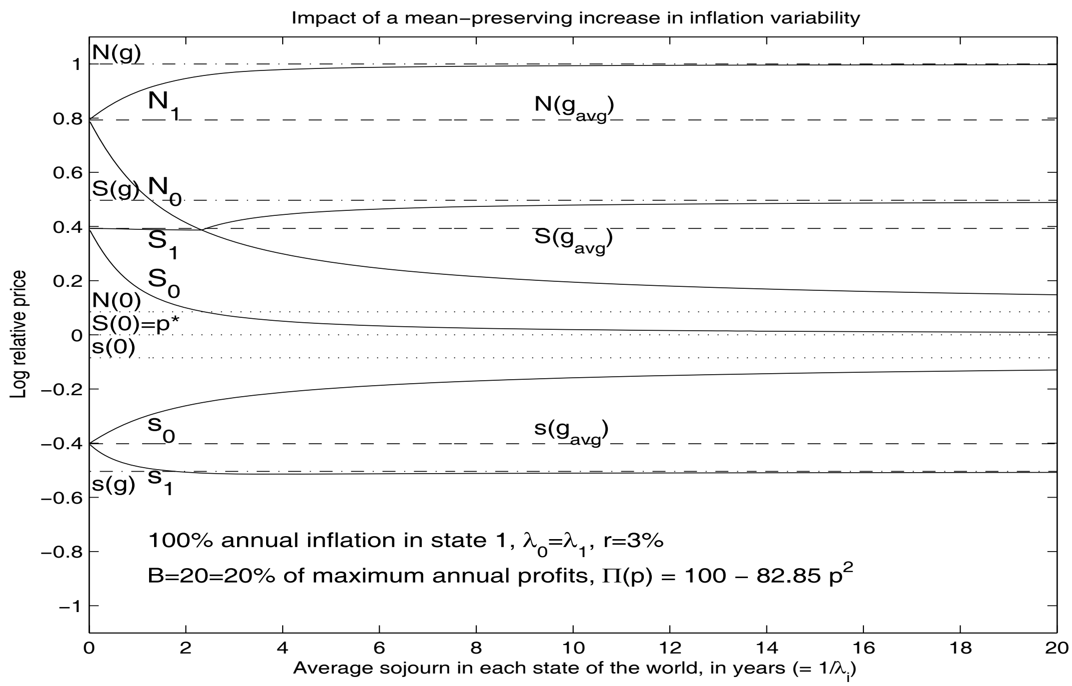

Figure 2: Higher inflation variability, captured by lower λ_i's, widens the state-1 inaction region and tightens the state-0 inaction region.

the high-inflation state bands. In particular, for high λ_i's, the parameters are quite similar across states and approximately equal to the parameters of a firm facing deterministic rate of inflation equal to the asymptotic average, $\overline{g} = g\lambda_0/(\lambda_0 + \lambda_1)$ (the dashed lines in Figure 2).[21] As the λ_i's decrease, persistence increases, and the parameters become more different across states. As intuition would suggest, the state-1 parameters approach those of a firm facing deterministic rate of inflation g (the dash-dotted lines in Figure 2) and the state-0 parameters approach those of a firm facing deterministic rate of inflation 0 (the dotted lines in Figure 2).

The results suggest that the more variable inflation, the greater the elasticity of the (s, S) bands to the current rate of inflation. However, the structure of uncertainty in this model links inflation variability with the persistence of inflation. This link may not hold in other specifications of uncertainty. For example, it would be interesting to see the relationship in the current setting augmented with i.i.d. shocks to each state's inflation rate.

[21] These and other parameters from the problem with deterministic inflation rate q (solved by SW77) are found by imposing optimality, value matching, and smooth pasting on the equation $rV(p) = \Pi(p) - qV'(p)$.

The results also make clear that setting $N_0 < S_1$ is sometimes optimal. Thus firms may lower their prices even though aggregate prices are monotonically increasing. Quite intuitively, if the persistence of inflation is strong enough, firms may find benefit in reducing their prices toward the optimal price when inflation stops.

4.2 Effect of Uncertainty on Firm Value

Value functions are graphed (using solid lines) in Figure 3. The left panel corresponds to $\lambda_0 = \lambda_1 = 1$, the right panel to $\lambda_0 = \lambda_1 = 1/4$; all other parameters for both panels are the same as for Figure 2. Also graphed (using dash-dotted lines) are the average of the value functions. This corresponds to the expected value of being at price p, not knowing the state, but with the probability of being in each state equal to the asymptotic expected fraction of time spent there.[22] We also graph (using dashed lines) the value of a firm facing deterministic inflation equal to the asymptotic average of the stochastic process, $\overline{g} = g\lambda_0/(\lambda_0 + \lambda_1)$.

Interestingly, in both examples, the expected value of the firm under stochastic inflation is higher than the value under the corresponding deterministic inflation rate. More remarkably, it is higher even when starting in the high-inflation regime. Evidently, the prospect of having zero-inflation spells in the future more than compensates for the current high rate of inflation. This effect gets stronger, not weaker, as the λ_i's decrease from 1 to 1/4 making inflation more persistent (and variable). It must be that the prospect of having longer zero-inflation spells in the future more than compensates for the prospect of having longer to endure in the current high inflation regime.

This effect is non-monotonic. As the λ_i's approach zero, the value function in state i converges to that of a firm facing deterministic drift ig, $i = 0, 1$. In this case, $V_0(p)$ would typically be above, and $V_1(p)$ below, the value of a firm facing deterministic drift $\overline{g} \in (0, g)$. In these cases too, most computational results place the expected value from the stochastic case everywhere higher than the value of deterministic drift $\overline{g}$. In fact, in nearly

[22] Specifically, the asymptotic probability of being in state 1 is $(1/\lambda_1)/(1/\lambda_1 + 1/\lambda_0)$ and of being in state 0 is $(1/\lambda_0)/(1/\lambda_1 + 1/\lambda_0)$. When $\lambda_0 = \lambda_1$, each probability is 1/2.

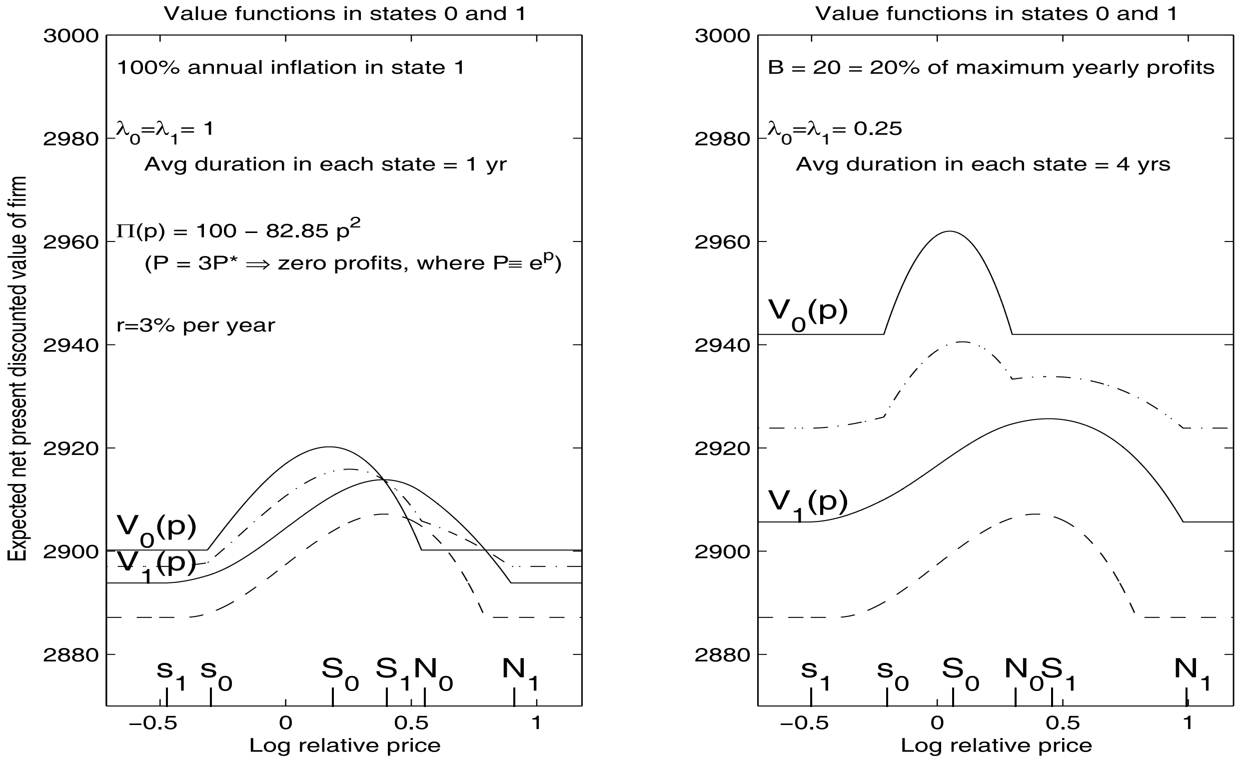

Figure 3: Value functions in states 0 and 1 (solid lines) and their average (dash-dotted lines), compared to firm value under constant inflation $\overline{g}$ equal to the average inflation in the stochastic case (dashed lines). All parameters except λ_0 and λ_1 are the same in both panels.

all parameterizations we try, the expected value of the stochastic case is higher than the value of deterministic drift $\overline{g}$. The only exceptions we found are when the λ_i's are high, in which case all value functions are nearly the same; and when g is near zero.

For robustness, we turn to the deterministic model of SW77. We compute the value of a firm at its optimal price, as a function of the deterministic drift rate g: $V[S(g);g]$. The value is decreasing and, as the above results would suggest, nearly everywhere convex in g; see Figure 4. The only exception is a concave portion near zero inflation;[23 24] for the above

[23]It is not surprising that the value $V[S(g);g]$ is concave at $g = 0$. It reaches a global maximum at $g = 0$, since no drift is better than inflation or deflation. Relatedly, we know from SW77 that $V[S(g);g] = \Pi[S(g)]/r$. Thus $dV/dg = S'(g)\,\Pi'[S(g)]/r$. Since $S(0) = p^*$, dV/dg must be zero at $g = 0$.

[24]Interestingly, firms are risk-averse over low levels of inflation, but risk-loving over high levels of inflation. If the range of inflation leading to risk aversion is non-negligible, this may imply that firms in low-inflation countries hedge against inflation more than firms in high-inflation countries.

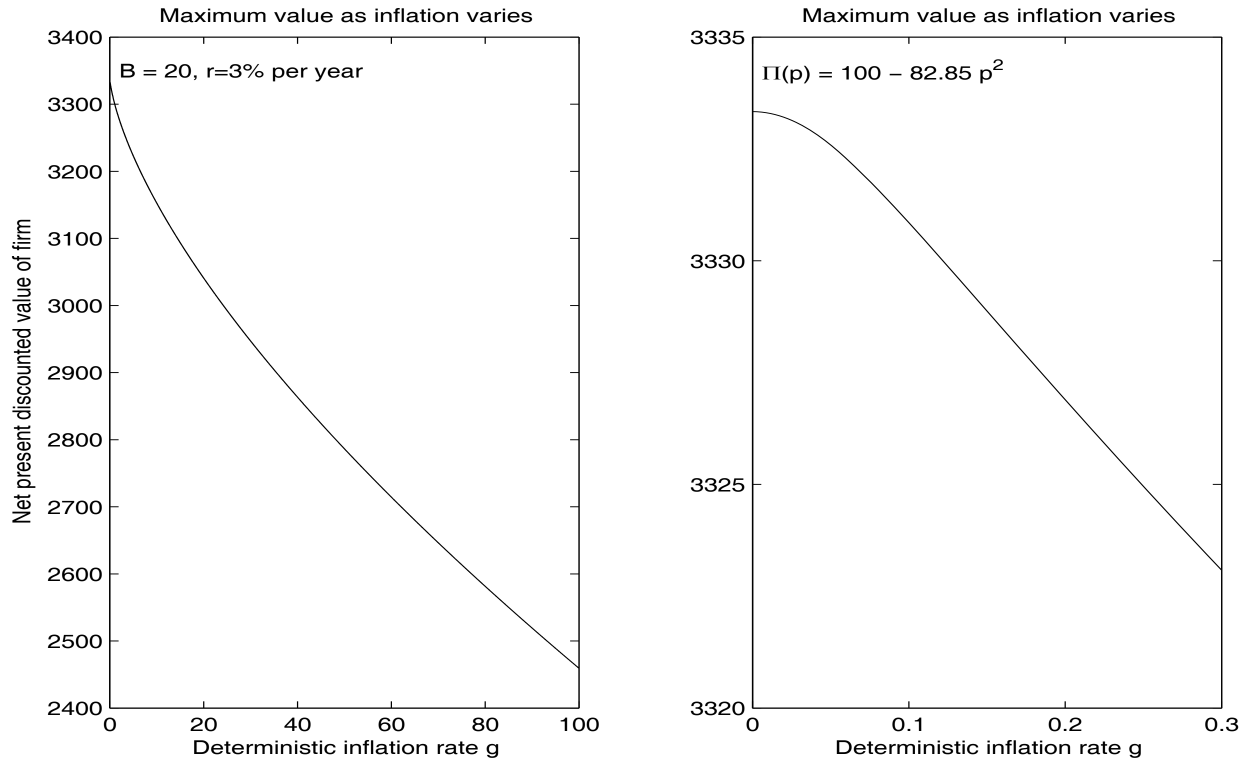

Figure 4: Certainty values as g varies. The right panel zooms in near $g = 0$.

parameters, the concave portion only appears for inflation less than 0.3% (detectable in the right panel of Figure 4). Thus in general, a firm would rather have a 50/50 lottery between facing g_1 forever and facing g_2 forever than face $(g_1 + g_2)/2$ forever.

These menu cost models generate risk-loving preferences with respect to inflation. The intuition appears to be as follows. If the drift rate doubles, the firm can always simply pay twice as much in menu costs over time, by keeping the same (s, S) band.[25] But it can do better by substituting between paying higher menu costs and accepting lower profits by widening its (s, S) band. Thus higher inflation lowers firm value, but in a convex way.

[25]This ignores discounting, but the basic thrust holds under discounting as well.

5 Empirical Results

5.1 Mexican Price Data and Main Results

There are several straightforward predictions of the model. First, price changes are larger in the high-inflation state of the world. Prices are adjusted from s_1 to S_1 in the high inflation state and from somewhere in $(s_1, s_0]$ to S_0 in the low-inflation state, and Proposition 1 establishes that $s_1 < s_0 < S_0 < S_1$. Second and relatedly, firms allow their relative prices to vary more widely in the high-inflation state. A firm's price will be contained (eventually) within $(s_1, S_1]$ in the high-inflation state. In the low-inflation state, it will be within $(s_0, S_1]$ if $S_1 < N_0$ or within (s_0, N_0) if $N_0 < S_1$. Since $s_1 < s_0$, the range of observable prices in the high-inflation state is wider than the range of prices in the low-inflation state.

Clearly, no real-world scenario fits the model's framework perfectly. For example, inflationary processes and expectations are not as simple as our two-state case with constant hazard rates, and low-inflation regimes rarely involve zero inflation as in the model. However, some scenarios are better candidates than others. The best case for finding evidence of the model's predictions would involve a large and sudden change from one persistent rate of inflation to another, and a public signal or event leading to a rapid shift in inflationary expectations. By contrast, small or transitory changes in inflation and inflationary expectations would not change the (s, S) bands by much, potentially leaving the model's predictions hard to detect in the data.

Hence we turn to the Mexican 'Tequila' crisis of early January 1995. In line with the model's framework of inflation regime alternation with constant exit probabilities, Mexico had seen periodic spells of high inflation, but the timing of this currency crisis was a relative surprise. It led to 52% inflation in 1995, the year after the crisis (and 28% in 1996), as compared with 7% in 1994, the year preceding the crisis (and 8% in 1993). Table 1 shows monthly inflation rates, π_t, in 1994 and 1995, based on the aggregate consumer price index (CPI), P_t. In light of the apparent large inflationary shift, we consider 1994 to be in the low-inflation regime and 1995 to be in the high-inflation regime.

[Table 1 about here]

Our raw Mexican micro price data, obtained from the Mexican Central Bank and hard-copy editions of "Diario Oficial", include all the establishment-level monthly prices used to compute the Mexican CPI, from January 1994 to October 1995.[26] From these, we chose a subset of goods, and establishments per good, as follows. We restricted attention to prices in Mexico City, the state with the most observations, for purposes of uniformity. Next, we eliminated all goods that did not have at least 14 observations with the exact same detailed product description in March 1995, the one month in our sample that included detailed product descriptions.[27] Since Mexican CPI sample sizes expanded during this period but before March 1995, we finally eliminated all goods that did not have at least 10 of these identical-product establishments represented in all 22 months. We were left with 44 goods, each with 10-22 price observations on products with identical descriptions for each of 22 months. Henceforth 'firm' is used in place of 'establishment'.

The goods are listed in Appendix Table A1 along with the number of firms per good. Table 1 also reports monthly inflation calculated using these 44 goods. In comparison with CPI inflation, it has more between-month variability mainly due to a smaller sample of goods, but matches annual CPI inflation fairly well.

Using this set of goods, we first examine how price change frequencies and magnitudes changed with the spike in inflation. For both, we distinguish between price changes and price

[26]We have data on November and December 1995 also. However, all prices for all the goods we use are exactly the same in November 1995 as in October 1995. We take this to be data error, and drop November. We drop December also since this eliminates the need to make several judgment calls, including about price change magnitudes and frequencies.

[27]Even within a good, the exact product sampled may vary. For example, the good 'tequila' had price samples from different brands, specifications, and quantities. (All prices are converted to a unit price, so quantity is important only if pricing is non-linear.) We took only subsets from each good with identical descriptions in all dimensions. For example, of the 26 observations on tequila, we end up with 14 observations, all brand 'Sauza', specification 'blanco' (white), and quantity of 1L. From a couple of goods, we end up with two different sets of products. For example, the good 'table wine' yields two different comparable sets of prices, for red and white wine, respectively. The exceptions to identical descriptions are when the variation in quantity was less than 10% (e.g. 940mL vs. 1L) and different shapes of pasta.

increases, since the model would predict only price increases.[28] Let F_{jt} (F^+_{jt}) be the fraction of firms selling good j that changed (increased) their price from time $t-1$ to t. For each good, time-average frequencies of price changes and increases in 1994 and 1995 are provided in Appendix Table A1. On the whole, the frequencies are a bit higher than those reported by Bils and Klenow (2004) for 350 categories of goods and services in the U.S. during the period 1995-1997.[29] Similarly, let M_{jt} (M^+_{jt}) be the average percentage price increase among those firms selling good j that changed (increased) price from time $t-1$ to t. For these variables, panel data become unbalanced since price change magnitudes are not observed if no firm changes price of a given good in a given month. Average magnitudes of price changes and increases are reported for each good in Appendix Table A1.

[Table 2 about here]

Table 2 reports the results of panel regressions, with good-specific fixed effects, of frequency and magnitude on a high-inflation regime dummy, D_t, which equals 1 if the month is in 1995. For all cases, the coefficients on the high-inflation regime dummies are significantly positive.[30] Price *increases* (F^+_{jt} and M^+_{jt}) are nearly eighty percent more frequent and nearly twenty percent larger, on average, in the high-inflation regime. Results for price *changes* (F_{jt} and M_{jt}) fit this pattern qualitatively but differ quantitatively mainly due to the non-negligible number of price decreases in 1994. Thus, the difference in frequencies of price changes across regimes is not as drastic as that of price increases, while the magnitudes are more different across regimes due to the negative changes in 1994.

Focusing on the price increase results, we find support for the first prediction of the

[28] The model allows for price decreases when inflation stops but not when it spikes upward, as is the case here.

[29] Of course, inflation was significantly lower in the U.S. than in Mexico during the respective periods. In addition, as Gagnon (2006) points out, there is an upward bias in the frequency numbers due to the fact that the price quotes are monthly averages. See Gagnon (2006) for a filter to eliminate this bias and for further analysis spanning eleven years of Mexican price data, including decomposition of inflation into frequencies and magnitudes of price changes.

[30] All regression tests in the paper are based on heteroskedasticity and autocorrelation robust standard errors for the fixed effects panel model (see Arellano, 1987). Similar results (not reported) are obtained using standard errors with the homoskedasticity assumption.

model. Had (s, S) bands not changed across regimes, all the inflation would come from increased frequency of price adjustment; however, a positive amount is coming from increased magnitudes of adjustment.

We next examine the second prediction, that firms allow prices to vary more widely when inflation is high. This is done by computing firm-specific long-run mean relative prices, and creating from them measures of dispersion that aggregate deviations from firms' own average prices rather than from other firms' average prices. The advantage of these measures is that according to the theory, they should increase with inflation regardless of heterogeneity or price synchronization across firms.

For each firm i, good j, and month t, the relative price is calculated as the firm price divided by the aggregate price index: $p_{ijt} = P_{ijt}/P_t$. The firm mean relative price is then calculated over the 22 months: $\overline{p}_{ij} = \sum_{t \in 1994,1995} p_{ijt}/22$. Regime-specific mean relative prices are also calculated: $\overline{p}_{ij,94} = \sum_{t \in 1994} p_{ijt}/12$ and $\overline{p}_{ij,95} = \sum_{t \in 1995} p_{ijt}/10$. One can interpret these $\overline{p}_{ij}$'s as estimates of the midpoints of firms' (s, S) bands. If the (s, S) bands have different midpoints across inflationary regimes, then using regime-specific $\overline{p}_{ij}$'s is the preferred approach.

We let $\delta_{ijt} = (p_{ijt} - \overline{p}_{ij})/\overline{p}_{ij}$ denote the percentage deviation of firm i's price in period t from its own long-run relative price. The following measures of dispersion are then calculated: (1) the mean squared deviation across firms: $MSD_{jt} = 100 \times \sqrt{\sum_i \delta_{ijt}^2 / \sum_i 1}$; (2) the mean absolute deviation: $MAD_{jt} = 100 \times \sum_i |\delta_{ijt}| / \sum_i 1$; (3) the range of deviations: $R_{jt} = 100 \times (\max_i\{\delta_{ijt}\} - \min_i\{\delta_{ijt}\})$; and (4) the interpercentile range based on the difference between the 90th and the 10th percentile deviations: $IPR_{jt} = 100 \times (Q_{90i}\{\delta_{ijt}\} - Q_{10i}\{\delta_{ijt}\})$. While the first two are more common measures of dispersion, we also consider the latter two since the literal prediction of the model involves a widened range. Also, note that MAD_{jt} and IPR_{jt} should reduce the effect of outliers relative to MSD_{jt} and R_{jt}, respectively. Finally, each of these measures can be calculated using either firms' regime-specific mean relative prices, $\overline{p}_{ij,94}$ and $\overline{p}_{ij,95}$, or firms' regime-invariant mean relative prices, $\overline{p}_{ij}$. This leaves eight measures.

[Table 3 about here]

Table 3 shows the results of panel regressions, with good-specific effects, of all dispersion measures on the regime dummy D_t or the aggregate monthly inflation rate π_t. Each entry represents one regression. The results with positive coefficients suggest that firms' distances from their own mean relative prices are higher when inflation is higher.

When regime-invariant mean relative prices ($\overline{p}_{ij}$) are used in the dispersion measures, all coefficients on both the regime dummy and the aggregate inflation rate are positive and significant. In the high inflation period, within-firm price variability increases by 2.5 percentage points on average for the first three dispersion measures, and by less than 2 percentage points on average for IPR_{jt}. In addition, a 1 percentage point increase in aggregate monthly inflation implies a 0.1-0.5 percentage point increase in price dispersion. When regime-specific mean relative prices ($\overline{p}_{ij,94}$ and $\overline{p}_{ij,95}$) are used, somewhat weaker evidence is obtained for the range measure R_{jt}. Coefficients on the regime dummy and aggregate inflation are not significantly different from zero. For the other three measures, however, the results are qualitatively and quantitatively similar to the regime-invariant mean relative price case. Among all four dispersion measures, the most consistently positive and significant measure is the IPR_{jt}, which focuses directly on the width of the (s, S) band but removes outliers. Overall, these regressions provide evidence for wider (s, S) bands in the high-inflation state.

5.2 Comparison to Previous Studies

Our analysis suggests price dispersion within a firm becomes higher in the high-inflation state. This result adds to a large literature on inflation and price dispersion. Most of the literature focuses, however, on the relationship between inflation and price dispersion *across* firms, rather than the dispersion *within* a firm. For example, Tommasi (1993) uses weekly data covering 15 goods, 5 sellers per good, and the time period of February to December 1990 in Argentina. Using inflation and its square, he finds some evidence for a positive relationship between inflation and the coefficient of variation of prices across firms, though the squared coefficient is negative. Reinsdorf (1994) finds a significant and robust negative relationship between inflation and price dispersion using U.S. data from the Volcker disinflation 1980 to 1982. Eden (2001) uses data from Israel and finds little significant relationship between price dispersion and inflation. Each study above uses good-specific inflation rates to measure inflation and uses price levels to measure dispersion.[31]

Are these results in line with our model? Similar to the prediction involving price dispersion within a firm (over time), the model can also imply greater dispersion of prices across firms selling a given good, in the high-inflation state. This third prediction of the model, however, can be considered weaker than the two in the previous subsection because it rests on two auxiliary assumptions. First, assume a number of firms identical except with respect to initial price. Second, assume that prices remain diffusely distributed (across firms) throughout the firms' identical inaction region. Under these assumptions, since the inaction region is larger in the high-inflation regime, the cross-section of prices will be more widely dispersed in the high-inflation state than in the low-inflation state. However, the prediction is not as clear-cut if firms are heterogeneous in (s, S) bands or if prices are not diffusely distributed (across firms) throughout the inaction region. Given the model's tendency toward price synchronization, discussed in section 3.3, the second assumption may be especially unlikely to hold. With these caveats in mind, we test this prediction regarding cross-sectional price dispersion, in part for purposes of comparison with the previous literature.

Our cross-firm measures of dispersion include: (1) the coefficient of variation, CV_{jt}, equal to the standard deviation of prices across firms selling good j at time t divided by the mean price across such firms at time t, $\overline{P}_{jt}$; (2) the range, $\widetilde{R}_{jt}$, given by the difference between the maximum and minimum prices of good j in month t, normalized by $\overline{P}_{jt}$; and (3) the

[31] There are also many studies that examine dispersion in price changes rather than price levels (see for example Lach and Tsiddon, 1992). We do not follow this approach here, in part because the implications of menu cost models for dispersion in price changes are less clear, as Reinsdorf (1994) points out.

interpercentile range, $\widetilde{IPR}_{jt}$, given by the difference between the 90th and the 10th percentile prices normalized by $\overline{P}_{jt}$.[32]

[Table 4 about here]

Table 4 shows the results of panel regressions, with good-specific fixed effects, of the three cross-firm dispersion measures on the regime dummy D_t or the aggregate monthly inflation rate π_t. In addition, we report results using the good-specific monthly inflation rate, π_{jt}, as the regressor, following the previous studies described above.[33] The prediction is not upheld but rather contradicted. At least when regressed on the regime dummy or the aggregate inflation rate, price dispersion is *lower* when inflation is high.

How do we reconcile these results with our previous findings? We interpret our rejection of the third prediction as a rejection of one or both of the auxiliary assumptions noted above, namely homogeneous firms and negligible price synchronization.

First, a closer look at the data makes clear that despite our attempts to eliminate product heterogeneity, firms do not appear to be following similar (s, S) bands. Some firms consistently price more highly than others. This could be explained by heterogeneity in location within Mexico City, for example. Thus there appears to be a substantial amount of price dispersion unrelated to menu costs.[34] As evidence, we test the hypothesis that mean relative prices over the 22-month sample period are identical across all firms selling a given good, using separate panel regressions for each good. This hypothesis is rejected at the one percent level for all forty four goods except vegetable shortening and instant coffee (as noted in Appendix Table A1).

[32]These measures remain unchanged if all prices increase by the same percentage.

[33]Which measure of inflation is more appropriate depends on the interpretation of the profit function in the model. The firm's real profits are plausibly a single-peaked function of the firm's price relative to the aggregate price index, since the price of all other goods in the economy affects both costs and real revenues. Ignoring the aggregate, it is also reasonable that a firm's real profits are a single-peaked function of the firm's price relative to the price index of the good it is selling, for example with monopolistic competition across similar firms. We prefer the latter measure, but run specifications using each one, in part for comparability to previous results.

[34]Golosov and Lucas (2005) conclude that much of observed pricing behavior is driven by idiosyncratic firm-specific shocks. Our data also indicate that existence of firm heterogeneity, in enduring price differences across firms.

Thus firms appear to have differently centered (s, S) bands. We note, however, that these bands appear to have converged somewhat after the regime changed. We compute the dispersion of $\overline{p}_{ij,94}$ and $\overline{p}_{ij,95}$ across firms i for each good j, using the coefficient of variation measure. Across goods, the average coefficient of variation in 1994 is 12.96 and in 1995 is 11.29. Indeed, more than two thirds of goods have higher dispersion of $\overline{p}_{ij,94}$ than of $\overline{p}_{ij,95}$. This at least partially explains why cross-firm dispersion decreased at the same time that firms allowed their prices to vary more widely: (s, S) bands grew wider within firms, while (s, S) band centers (and optimal prices) converged across firms.[35]

Second, it may be that price synchronization increased after the crisis, decreasing cross-firm price dispersion even though (s, S) bands widened. This is not predicted by the model, since synchronization only increases after inflation stops. But a richer model that included monopolistic competition and endogenously varying substitution elasticities (due to search effects, say) might explain this. Alternatively, there would be a clear force for increased synchronization if firm pricing became more influenced by public signals after the crisis.

In summary, firms changed their prices by more and allowed their prices to vary more widely when inflation was high. Cross-firm price dispersion declined, but this appears to be due to decreased firm heterogeneity rather than narrower (s, S) bands. The analysis here goes beyond previous work in examining dispersion measures that allow for firm heterogeneity. Specifically, these measures use deviations from firms' own long-run average prices rather than from other firms' average prices. Results of these tests support the idea that the menu-cost component of price dispersion did increase with inflation.

[35]Why this occurred is beyond the scope of this paper. Some possibilities are that differentiation decreased when inflation increased because firms were basing their pricing more on public signals (such as international prices and exchange rates) and less on private information; or because consumers spent more time searching or shopping, reducing firms' locational advantages (though this may be incompatible with reduced overall price dispersion).

6 Conclusion

The model studied here, due to SW83, is relatively unique in the state-dependent pricing literature in treating an inflation rate that persistently deviates from trend. Its solution is more complicated than previously thought. The firm will operate two different (s, S) bands depending on the inflationary state of the world – engaging in state-dependent state-dependent pricing. The low-inflation band is narrower than the high-inflation band. The effect of uncertainty is not to widen the (s, S) band per se, but to increase the elasticity of its width to the current rate of inflation. A striking implication of this model is that firms appear to prefer inflation risk in many circumstances.

Firms' use of multiple (s, S) bands has implications for aggregate behavior. It creates a force for bunching of prices, making a uniform distribution impossible to maintain. It thus would lead to real effects of money in a model such as that of Caplin and Spulber (1987). Use of multiple bands appears likely to be optimal whenever the stochastic component of inflation is persistent.

The data from Mexico's Tequila crisis do suggest that firms use different (s, S) bands depending on the inflationary state of the world. After inflation increased in a dramatic and unexpected way, firms changed prices by more and allowed their prices to stray further from their respective optima.

It may well be fruitful to pursue in greater detail aggregate implications under conditions of a Markov money growth process and varying (s, S) bands. One could look at inflation and output effects monetary regime changes varying by size of shock (g) and different degrees of credibility (λ_0, λ_1). If the intuition derived from this model holds, this simple framework could produce real effects from an increase in the growth rate of the money supply, and persistence in inflation and negative real effects after a decrease in the growth rate of the money supply.

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A Appendix

Proof of Lemma 1. From equation 2, $V_1(p)$ is continuous and differentiable on the interior of A_1. An equation analogous to equation 4 can be written for every p in the interior of I_1. Inspection of equation 4 gives that $V_1(p)$ is continuous in p (even if $V_0(p)$ is not). Thus $V_1(p)$ is continuous on the interior of I_1. This also implies that in the interior of I_1, $V_0(p)$ is continuous in p, it being the maximum of two functions continuous in p (see equations 2 and 6). Thus, since all functions on the right-hand side of equation 5 are continuous in the interior of I_1, V_1 is differentiable in the interior of I_1.

Next, assume V_1 is continuous on boundary points between A_1 and I_1. Then V_1 is continuous everywhere. This implies that V_0 is also continuous everywhere, since it is the maximum of two functions continuous in p (see equations 2 and 6). Continuity of both functions then implies that both inaction regions consist of one or more convex, open intervals, since the inaction regions can be defined by $I_i = \{p : V_i(p) > V_i(S_i) - B\}$. Finally, inspection of equations 2 and 6 establishes that V_0 is also differentiable everywhere on the interior of A_0 and I_0, except (potentially) at points in I_0 where V_1 is not differentiable, that is, points on the boundary of A_1.

Finally, we show V_1 continuous at arbitrary boundary point p. If $(p-\epsilon, p) \subset A_1$ and $(p, p+\epsilon) \subset I_1$ for $\epsilon > 0$ small enough, then clearly $V_1(p)$ equals $V_1(S_1) - B$ since profits will be enjoyed for a measure-zero time span before the price change occurs. The limits from both sides of p then also equal $V_1(S_1) - B$ (see equations 2 and 4). This implies continuity. If $(p-\epsilon, p) \subset I_1$ and $(p, p+\epsilon) \subset A_1$ for $\epsilon > 0$ small enough, then it must also be that $V_1(p)$ and the limits from both sides of p equal $V_1(S_1) - B$. If not, the limit from the left must be strictly higher or lower than the value of action. Take the former case. Then one can choose a δ such that inaction over $(p-\epsilon, p+\delta)$, at least until the regime changes or the price is raised, leads to higher value over $(p, p+\delta)$. This is due to continuity with respect to p in equation 4, and contradicts optimality. In the latter case, this implies the value at some points in the inaction region is strictly less than the value of action, a contradiction of optimality. Thus V_1 is continuous at boundary point p.[36] ■

Proof of Lemma 3. Let s_1 be the lower bound of an open interval contained in I_1, and assume $s_1 > p^*$. We consider three cases, each of which leads to contradiction. First, assume s_1 is in the interior of A_0. Then there is an $\epsilon > 0$ such that $(s_1, s_1 + 2\epsilon) \subset I_1 \cap A_0$, $(s_1 - 2\epsilon, s_1) \subset A_1 \cap A_0$, and $s_1 - \epsilon > p^*$. Using equation 4, we can write

$$V_1(s_1+\epsilon) = e^{\frac{-R_1\epsilon}{g}}[V_1(S_1)-B] + \int_0^\epsilon e^{\frac{-R_1(\epsilon-u)}{g}} \left[\frac{\Pi(s_1+u)+\lambda_1[V_0(S_0)-B]}{g}\right] du > V_1(S_1)-B.$$

This expression uses a change of variables $u = z - q$ in the integration, the fact that the neighborhood of s_1 is in A_0 so $V_0(u) = V_0(S_0) - B$, and the fact that $V_1(s_1) = V_1(S_1) - B$ since once s_1 is reached, the price will be changed to S_1. Now consider temporary inaction over $(s_1 - \epsilon, s_1]$, reverting back to original policy after either the regime changes or a price change is made. The value from this policy can be written similarly as

$$\hat{v}_1(s_1) = e^{\frac{-R_1\epsilon}{g}}[V_1(S_1)-B] + \int_0^\epsilon e^{\frac{-R_1(\epsilon-u)}{g}} \left[\frac{\Pi(s_1-\epsilon+u)+\lambda_1[V_0(S_0)-B]}{g}\right] du.$$

Since $\Pi(s_1 - \epsilon + u) > \Pi(s_1 + u)$ for $u \in (0, \epsilon)$ by strict concavity of Π and the fact that $s_1 - \epsilon > p^*$, it is clear that $\hat{v}_1(s_1) > V_1(s_1+\epsilon)$ $(> V_1(S_1)-B)$. This contradicts the optimality of action at s_1.

Second, assume s_1 is in the interior of I_0. Then for some $\epsilon > 0$, $(s_1, s_1 + 2\epsilon) \subset I_1 \cap I_0$, $(s_1 - 2\epsilon, s_1) \subset A_1 \cap I_0$, and $s_1 - \epsilon > p^*$. In $I_1 \cap I_0$, equations 5 and 6 can be solved

[36] We have not addressed the pathological case where even an arbitrarily small half-ball above or below p contains prices in both A_1 and I_1. In such a case, we can treat all points in I_1 that do not have a positive-measure interval of I_1 immediately to the left as in A_1; this is because profits will be enjoyed for a measure-zero time span before the price change occurs. Thus we only need be concerned with interval subsets of I_1 near p, and in particular, with the question of whether restricting attention to these subsets gives a limit approaching p other than $V_1(S_1) - B$. Note that any such interval must be continuous at its left endpoint, by inspection of equation 4. Further, the slope of V_1 in the inaction region interior, given in equation 5, is clearly bounded above since Π and V_0 are. Thus it is clear that for any $\delta > 0$, a tight enough half-ball can be found that restricts V_1 from rising more than δ above $V_1(S_1) - B$. (We need not be concerned about going below $V_1(S_1) - B$, since this would contradict optimality.) Thus the limit on this half-ball exists and equals $V_1(S_1) - B$. One can use the same logic as in the text to prove continuity in this case, where the half-ball is treated analogously to a half-ball completely contained in A_1.

simultaneously to get

$$rV_1(p) = \Pi(p) - g_1 V_1'(p), \tag{14}$$

where $g_1 \equiv g(r+\lambda_0)/(r+\lambda_0+\lambda_1)$. This differential equation yields the solution

$$V_1(s_1+\epsilon) = e^{\frac{-r\epsilon}{g_1}}[V_1(S_1) - B] + \int_0^\epsilon e^{\frac{-r(\epsilon-u)}{g_1}} \left[\frac{\Pi(s_1+u)}{g_1}\right] du > V_1(S_1) - B,$$

using techniques of the previous paragraph. Now let $\hat{v}_1$ be defined on $(s_1-\epsilon, s_1)$ as the value of temporarily deviating to inaction over this interval, returning to the original plan after a price change or regime change. One can show that the following equation (analogous to equation 5) applies over this interval:

$$R_1\hat{v}_1(p) = \Pi(p) + \lambda_1 V_0(p) - g\hat{v}_1'(p).$$

This can be solved simultaneously with equation 6 to get

$$r\hat{v}_1(p) = \Pi(p) - g_1\hat{v}_1'(p) + \frac{\lambda_0\lambda_1}{r+\lambda_0+\lambda_1}\left[V_1(p) - \hat{v}_1(p)\right].$$

Define the last term as $\theta(p)$. By hypothesis, the deviation represented in $\hat{v}_1(p)$ cannot raise firm value, and thus $\theta(p) \geq 0$. As above, we can write

$$\hat{v}_1(s_1) = e^{\frac{-r\epsilon}{g_1}}[V_1(S_1) - B] + \int_0^\epsilon e^{\frac{-r(\epsilon-u)}{g_1}} \left[\frac{\Pi(s_1-\epsilon+u)+\theta(s_1-\epsilon+u)}{g_1}\right] du > V_1(s_1+\epsilon).$$

The inequality, due to reasoning as in the previous paragraph, contradicts optimality of action at s_1.

Third, assume s_1 is on the boundary between I_0 and A_0. First assume s_1 is on a lower boundary of A_0. An argument exactly analogous to that of the first case can be applied to establish a contradiction. The only difference is that in the expression for $v_g^*(s_1)$, $V_0(u)$ will not equal $V_0(S_0) - B$, the value of action, but something larger. This only strengthens the case. Second assume s_1 is on an upper boundary of A_0. Then using equation 6 and applying lemma 2 (smooth pasting) give that $\lim_{z\downarrow s_1} V_0'(z) = \Pi'(s_1)/R_1$, strictly negative for $s_1 > p^*$. Since $V_0(s_1) = V_0(S_0) - B$, this implies that the value in state 0 goes below $V_0(S_0) - B$, a contradiction of optimality. Thus, any lower boundary of an inaction interval must be no greater than p^*: $s_1 \le p^*$.

Next, let (s_1, N_1) be an open interval contained in I_1, bounded on both ends by A_1, and assume $N_1 \le p^*$. By continuity and equation 5

$$R_1 V_1(N_1) = \Pi(N_1) + \lambda_1 V_0(N_1) - g \lim_{z\uparrow N_1} V_1'(z).$$

Optimality implies that $\lim_{z\uparrow N_1} V_1'(z)$ be non-positive; otherwise, the value would drop below the value of action. Thus

$$\Pi(N_1) \le R_1 V_1(N_1) - \lambda_1 V_0(N_1).$$

A similar expression holds at s_1, except with equality due to smooth pasting:

$$\Pi(s_1) = R_1 V_1(s_1) - \lambda_1 V_0(s_1).$$

Since $s_1 < N_1 \le p^*$ and Π is strictly concave, $\Pi(N_1) > \Pi(s_1)$. Further, by continuity both $V_1(s_1)$ and $V_1(N_1)$ equal $V_1(S_1) - B$. Combining these facts with the above expressions gives that $V_0(s_1) > V_0(N_1)$. This is impossible if $s_1 \in A_0$, since the value in state 0 is bounded below by the value of action. Thus equation 6 applies at s_1, and

$$\frac{\Pi(s_1) + \lambda_0 V_1(s_1)}{R_0} = V_0(s_1) > V_0(N_1) \ge \frac{\Pi(N_1) + \lambda_0 V_1(N_1)}{R_0},$$

where the last inequality is because the state-0 value at N_1 is at least as great as the value of inaction there. But since $V_1(s_1) = V_1(N_1)$ as noted above, this implies that $\Pi(s_1) > \Pi(N_1)$, a contradiction. Thus any upper bound of an interval in I_1 must be strictly greater than p^*: $p^* < N_1$. Since any lower bound must be no greater than p^*, this establishes that

$I_1 = (s_1, N_1)$.

We now turn to state-0 policy. Let s_0 be the lower bound of an open interval contained in I_0, and assume $s_0 > p^*$. There exists an $\epsilon > 0$ such that $(s_0 - 2\epsilon, s_0) \subset A_0$ and $p^* < s_0 - \epsilon$. Then

$$\frac{\Pi(s_0 - \epsilon) + \lambda_0 V_1(s_0 - \epsilon)}{R_0} \leq V_0(S_0) - B = V_0(s_0) = \frac{\Pi(s_0) + \lambda_0 V_1(s_0)}{R_0}.$$

The first inequality is because $(s_0 - \epsilon) \in A_0$ and thus the value of inaction there (from equation 6) is no greater than the value of action. The equalities are because both equations 2 and 6 apply at boundary points due to continuity. Since $\Pi(s_0 - \epsilon) > \Pi(s_0)$ due to strict concavity of Π and the fact that $p^* < s_0 - \epsilon < s_0$, it must be that $V_1(s_0) > V_1(s_0 - \epsilon)$. This can only be true if $s_0 \in I_1$ since V_1 is bounded below at $V_1(S_1) - B$.

Thus there is an $\epsilon > 0$ such that $(s_0, s_0 + 2\epsilon) \subset I_0 \cap I_1$, $(s_0 - 2\epsilon, s_0) \subset A_0 \cap I_1$, and $s_0 - \epsilon > p^*$. In $I_0 \cap I_1$, equations 5 and 6 can be solved simultaneously to yield

$$rV_0(p) = \Pi(p) + (g_1/R_0)\Pi'(p) - g_1 V_0'(p),$$

with g_1 defined above. This differential equation yields the solution

$$V_0(s_0+\epsilon) = e^{\frac{-r\epsilon}{g_1}}[V_0(S_0) - B] + \int_0^{\epsilon} e^{\frac{-r(\epsilon-u)}{g_1}} \left[\frac{\Pi(s_0+u)}{g_1} + \frac{\Pi'(s_0+u)}{R_0}\right] du > V_0(S_0) - B, \quad (15)$$

by reasoning above. Now let $\hat{v}_0$ be defined on $(s_0 - \epsilon, s_0)$ as the value of temporarily deviating to inaction over this interval, returning to the original plan after a price change or regime change. The following analogue to equation 6 applies over this interval:

$$\hat{v}_0(p) = [\Pi(p) + \lambda_0 V_1(p)]/R_0.$$

This can be solved simultaneously with equation 5 to get

$$r\hat{v}_0(p) = \Pi(p) + (g_1/R_0)\Pi'(p) - g_1 \hat{v}_0'(p) + \frac{\lambda_0 \lambda_1}{r + \lambda_0 + \lambda_1}\left[V_0(p) - \hat{v}_0(p)\right].$$

Define the last term as $\theta(p)$. By hypothesis, the deviation represented in $\hat{v}_0(p)$ cannot raise firm value, and thus $\theta(p) \geq 0$. As above, we can write

$$\hat{v}_0(s_0) = e^{\frac{-r\epsilon}{g_1}}[V_0(S_0) - B] + \int_0^{\epsilon} e^{\frac{-r(\epsilon-u)}{g_1}} \left[\frac{\Pi(s_0 - \epsilon + u) + \theta(s_0 - \epsilon + u)}{g_1} + \frac{\Pi'(s_0 - \epsilon + u)}{R_0}\right] du.$$

Since both $\Pi(p)$ and $\Pi'(p)$ are declining in p above p^*, comparing this with equation 15 establishes that $\hat{v}_0(s_0) > V_0(s_0 + \epsilon)$. This contradicts optimality of action at s_0. Thus any lower boundary of an inaction interval must be no greater than p^*: $s_0 \leq p^*$.

Finally, let (s_0, N_0) be an open interval contained in I_0, bounded on both ends by A_0, and assume $N_0 \leq p^*$. An argument similar to the one above concerning N_1 gives that $V_1(s_0) > V_1(N_0)$. This implies that $s_0 \in int(I_1)$. The result above that $I_1 = (s_1, N_1)$ with $p^* < N_1$ further implies that $(s_0, N_0) \subset I_1$. Thus we can apply equation 4:

$$V_1(N_0) = e^{\frac{-R_1(N_0 - s_0)}{g}} V_1(s_0) + \int_{s_0}^{N_0} e^{\frac{-R_1(N_0 - z)}{g}} \left[\frac{\Pi(z) + \lambda_1 V_0(z)}{g}\right] dz.$$

Using this along with the facts $V_1(s_0) > V_1(N_0)$, $\Pi(z) > \Pi(s_0)$ for $z \in (s_0, N_0)$ (since Π is strictly concave and $N_0 < p^*$), and $V_0(z) > V_0(s_0)$ for $z \in (s_0, N_0)$, we can write

$$V_1(s_0) > \frac{\int_{s_0}^{N_0} e^{\frac{-R_1(N_0 - z)}{g}} \left[\frac{\Pi(z) + \lambda_1 V_0(z)}{g}\right] dz}{1 - e^{\frac{-R_1(N_0 - s_0)}{g}}} > \frac{\Pi(s_0) + \lambda_1 V_0(s_0)}{R_1}. \tag{16}$$

Since $s_0 \in int(I_1)$, (s_1, s_0) is a non-empty subset of $I_1 \cap A_0$. Using the fact that $(s_1, s_0) \subset A_0$, we can use equation 5 to write $R_1 V_1(p) = \Pi(p) + \lambda_1 V_0(s_0) - g V_1'(p)$ for p in this interval. Differencing and using smooth pasting gives

$$R_1[V_1(p) - V_1(s_1)] = \Pi(p) - \Pi(s_1) - g V_1'(p).$$

This can be solved to yield

$$V_1(s_0) = V_1(s_1) + \int_{s_1}^{s_0} e^{\frac{-R_1(s_0-z)}{g}} \frac{\Pi(z) - \Pi(s_1)}{g} dz > V_1(s_1),$$

where the inequality is due to the fact that $\Pi(z) > \Pi(s_1)$ for $z \in (s_1, s_0)$, for familiar reasons. But now we can use similar logic to that leading up to equation 16 to write

$$V_1(s_0) < \frac{\int_{s_1}^{s_0} e^{\frac{-R_1(s_0-z)}{g}} \left[\frac{\Pi(z)+\lambda_1 V_0(z)}{g}\right] dz}{1 - e^{\frac{-R_1(s_0-s_1)}{g}}} < \frac{\Pi(s_0) + \lambda_1 V_0(s_0)}{R_1}.$$

This contradicts equation 16. Thus any upper bound of an interval in I_0 must be strictly greater than p^*: $p^* < N_0$. Since any lower bound must be no greater than p^*, this establishes that $I_0 = (s_0, N_0)$.

It remains to show that s_0 and s_1 are *strictly* less than p^*. Equation 2 gives that $V_0(S_0) - V_0(s_0) = B$. Using equation 6, we can write

$$\Pi(S_0) - \Pi(s_0) = \lambda_0\{B - [V_1(S_0) - V_1(s_0)]\} + rB > 0.$$

The inequality holds because the difference in value between any two points cannot exceed B, and thus the bracketed term cannot be negative. Thus $\Pi(s_0) < \Pi(S_0)$. Since $s_0 < S_0$ (S_0 must be in I_0) and given that Π is strictly concave and maximized at p^*, it must be that $s_0 < p^*$. An exactly parallel argument (making use of smooth pasting) shows $s_1 < p^*$. ■

Proof of Lemma 4. Consider first state 1. Of course there exists at least one local maximum over I_1; otherwise every price would lead to action, which cannot be optimal. Here we prove there is only one local maximum in I_1, which is then a global maximum.

First, consider the following subset of I_1: $I_1 \cap I_0$. Differentiating equation 14, which applies over this region, gives

$$rV_1'(p) = \Pi'(p) - g_1 V_1''(p). \tag{17}$$

The first- and second-order conditions for a local maximum at p imply that $\Pi'(p) < 0$, which requires $p > p^*$. Now, suppose S_1^a and $S_1^b > S_1^a$ are two local maxima in $I_1 \cap I_0$. Then there must exist local minimum at S_1^c, say, with $S_1^a < S_1^c < S_1^b$ and $V_1(S_1^c) < V_1(S_1^b)$. Again using equation 14, note that $V_1(S_1^b) = \Pi(S_1^b)/r$ and $V_1(S_1^c) = \Pi(S_1^c)/r$. This implies $\Pi(S_1^c) < \Pi(S_1^b)$, a contradiction since $p^* < S_1^a < S_1^c < S_1^b$. Thus there is at most one local maximum in $I_1 \cap I_0$, and it must strictly exceed p^*.

Second, consider the following subset of I_1: $I_1 \cap A_0 \cap (-\infty, p^*)$. Even if non-empty, this subset cannot contain a local maximum. Note that equation 5 can be differentiated on this interval to give

$$R_1 V_1'(p) = \Pi'(p) - gV_1''(p),$$

since $V_0(p)$ is constant. Given that $p < p^*$, $\Pi'(p) > 0$ and any local extremum cannot be a local maximum.[37]

Third, consider the remaining subset of I_1, which equals $I_1 \cap A_0 \cap (p^*, \infty)$. Suppose there are two local maxima on this interval, S_1^a and $S_1^b > S_1^a$, say. Then there must exist a local minimum at S_1^c, say, with $S_1^a < S_1^c < S_1^b$ and $V_1(S_1^c) < V_1(S_1^b)$. But using equation 5 and the fact that $S_1^c, S_1^b \in A_0$, one can show this implies that $\Pi(S_1^c) < \Pi(S_1^b)$. This is a contradiction, since $p^* < S_1^a < S_1^c < S_1^b$ and Π is strictly concave. Thus there is at most one local maximum in $I_1 \cap A_0 \cap (p^*, \infty)$.

We have established that there are at most two local maxima, one in $I_1 \cap I_0$ the other in $I_1 \cap A_0 \cap (p^*, \infty)$, and that both strictly exceed p^*. We now show there can be at most one local maximum. Suppose there are two, $S_1^a \in I_1 \cap I_0$ and $S_1^b \in I_1 \cap A_0$; clearly $p^* < S_1^a < S_1^b$.

[37] This applies except on the boundary of A_0, i.e. at $p = s_0$, where V_0 may not be differentiable. But the same argument can be modified using the left and right limits of the second derivative at s_0. In particular, $\lim_{p \uparrow s_0} V_0'(p) = 0$ and $\lim_{p \downarrow s_0} V_0'(p) \geq 0$ since otherwise the value in state 0 would drop below the value of action. Given this, both $\lim_{p \uparrow s_0} V_0''(p)$ and $\lim_{p \downarrow s_0} V_0''(p)$ are strictly positive, ruling out a local maximum.

Then there exists a local minimum S_1^c, say, with $S_1^a < S_1^c < S_1^b$ and $V_1(S_1^c) < V_1(S_1^b)$. But if $S_1^c \in A_0$, the argument of the previous paragraph implies that $\Pi(S_1^c) < \Pi(S_1^b)$, a contradiction. If $S_1^c \in I_0$, then equation 17 applies and gives that $V_1''(S_1^c) < 0$, which contradicts S_1^c's being a local minimum. Thus, there is exactly one local maximum in I_1, $S_1 > p^*$.

Consider next state 0, and the following subset of I_0: $I_0 \cap A_1$. Everywhere on this set, except (potentially) at N_1, $V_1'(p) = 0$. Thus using equation 6, $R_0 V_0'(p) = \Pi'(p)$ except (potentially) at N_1. This is clearly non-zero, since $p^* \notin A_1$. Similarly, $\lim_{p \downarrow N_1} R_0 V_0'(p) = \Pi'(N_1) < 0$ and $\lim_{p \uparrow N_1} R_0 V_0'(p) = \Pi'(N_1) + \lim_{p \uparrow N_1} \lambda_0 V_1'(p) < 0$. The latter inequality holds in part because the second term is non-positive, since otherwise V_1 would go below the value of action. Thus there is no local maximum on $I_0 \cap A_1$.

Consider finally $I_0 \cap I_1$. Again using equation 6, $R_0 V_0'(p) = \Pi'(p) + \lambda_0 V_1'(p)$. Clearly there can be no maximum for $p < p^*$, since $\Pi'(p) > 0$ and $V_1'(p) \geq 0$. There can also be no maximum for $p \geq S_1$, since $\Pi'(p) < 0$ and $V_1'(p) \leq 0$. Further, there can be no maximum at p^*. This would require $V_1'(S_1) = 0$ (which might be possible at a point of inflection); but then solving equations 6 and 5 simultaneously would give $V_1(S_1) = \Pi(p^*)/r$, which we know is impossible. Thus any maximum must be in $(p^*, S_1) \cap I_0$.

Note that over $(p^*, S_1) \cap I_0$, V_1 is strictly concave. This can be seen by differentiating equation 14 and rearranging to get

$$g_1 V_1''(p) = \Pi'(p) - r V_1'(p).$$

Clearly in this range, $\Pi'(p) < 0$ and $V_1'(p) \geq 0$. Differentiating equation 6 twice then gives

$$R_0 V_0''(p) = \Pi''(p) + \lambda_0 V_1''(p).$$

This is strictly negative since Π is strictly concave, as is V_1 over this range. Thus there is exactly one local maximum in I_0, $S_0 \in (p^*, S_1)$. ■

Proof of Lemma 6. By reasoning as in the proof of lemma 5, we know that $V_0(N_1) \geq V_0(S_0) - B > V_1(S_1) - B = V_1(N_1)$. Now if $N_1 \leq N_0$, then N_1 is on the boundary or in the interior of both states' inaction regions. Thus the inaction region value functions 6 and a version of 5 apply at N_1:

$$R_1 V_1(N_1) = \Pi(N_1) + \lambda_1 V_0(N_1) - g \lim_{p \uparrow N_1} V_1'(p).$$

Solving them simultaneously gives that

$$(r + \lambda_0 + \lambda_1)[V_0(N_1) - V_1(N_1)] = g \lim_{p \uparrow N_1} V_1'(p).$$

This is a contradiction; we have shown the left-hand side strictly positive, while the right-hand side must be non-positive since $V_1(\cdot)$ reaches a minimum at N_1. ■

Proof of Lemma 7. Equation 5 gives that $V_1(S_1) = [\Pi(S_1) + \lambda_1 V_0(S_1)]/R_1$. Now if $S_1 \geq N_0$, then S_1 is in A_0: $V_0(S_1) = V_0(S_0) - B$. Using equation 6 to get $V_0(S_0)$ and combining this with the expression for $V_1(S_1)$ gives

$$(R_1/\lambda_1)V_1(S_1) - (\lambda_0/R_0)V_1(S_0) = \Pi(S_1)/\lambda_1 + \Pi(S_0)/R_0 - B.$$

Since $V_1(S_1) > V_1(S_0)$, $V_1(S_1) \geq 0$, and $R_1/\lambda_1 > 1 > \lambda_0/R_0$, the left-hand side is strictly positive. Thus

$$0 < \Pi(S_1)/\lambda_1 + \Pi(S_0)/R_0 - B < \Pi(p^*)/\lambda_1 + \Pi(p^*)/R_0 - B.$$

This contradicts assumption A1. Therefore, $S_1 < N_0$. ■

Table A1 — List of Goods and Monthly Average of Price Increase/Change

	Number	Frequency of				Magnitude of			
	of	price increase		price change		price increase		price change	
Good (English Equivalent)	firms	1994	1995	1994	1995	1994	1995	1994	1995
1. Harina de maiz (Corn flour)	10	5.5	35.0	12.7	39.0	7.1	7.8	0.1	5.1
2. Pan de caja (Bread)	15	20.6	81.3	23.6	82.7	5.2	5.1	1.8	5.0
3. Pan blanco (White bread)	15	62.4	75.3	90.9	89.3	4.4	9.8	2.2	9.1
4. Pan dulce (Sweet bread)	15	55.2	76.0	96.4	85.3	3.3	6.7	0.9	6.0
5. Pasta para sopa (Pasta)	22	11.2	51.4	18.6	53.2	7.1	9.0	1.7	8.5
6. Higado de res (Liver)	12	1.5	15.8	2.3	16.7	6.9	11.6	0.0	10.5
7. Chuleta (Pork chopsv)	12	22.0	31.7	34.8	43.3	4.7	6.5	0.6	5.1
8. Lomo (Pork loin)	12	23.5	26.7	36.4	38.3	5.9	4.4	1.9	3.7
9. Pollo entero (Whole chicken)	12	28.8	32.5	65.9	72.5	4.9	6.5	-0.6	1.7
10. Pollo en piezas (Chicken pieces)	12	38.6	42.5	75.0	79.2	4.4	4.4	-0.3	1.0
11. Atun en lata (Canned tuna)	10	17.3	51.0	25.5	57.0	4.7	7.7	1.0	5.2
12. Otros pesc. y maris. en co (Other canned fish/seafood)	10	5.5	43.0	7.3	48.0	6.4	12.6	1.9	10.3
13. Leche en polvo (Powdered milk)	12	19.7	63.3	29.5	65.8	3.5	6.7	0.7	6.4
14. Leche evaporada (Evaporated milk)	15	12.1	72.7	24.8	76.0	2.5	7.2	-0.8	6.7
15. Leche condensada (Condensed milk)	15	12.1	73.3	16.4	76.0	4.4	6.2	1.6	5.9
16. Mantequilla (Butter)	14	19.5	53.6	31.8	53.6	7.5	9.2	0.5	9.2
17. Manteca vegetal (Vegetable Shortening)[1,5,10]	15	25.5	64.0	37.0	64.7	5.4	10.9	2.3	10.5
18. Manteca de cerdo (Lard)	13	2.1	51.5	3.5	53.1	14.8	11.7	5.9	11.1
19. Margarina (Margarine)	12	26.5	40.8	33.3	40.8	7.5	14.4	4.4	14.4
20. Platano tabasco (Banana)	15	34.5	52.0	65.5	70.0	9.2	10.0	-0.4	5.9
21. Papaya (Papaya)	12	29.5	56.7	65.9	75.0	12.9	19.1	-1.5	10.4
22. Melon (Melon)	12	43.2	53.3	90.9	89.2	11.5	18.8	-0.6	6.5
23. Sandia (Watermelon)	12	31.1	48.3	71.2	82.5	15.2	9.9	-0.8	3.4
24. Chile serrano (Chile)[1]	15	35.2	50.0	83.6	92.0	17.8	19.4	-1.9	5.4
25. Chile poblano (Chile)	15	49.1	44.7	92.7	96.0	20.4	17.9	2.9	1.6
26. Cebolla (Onion)	14	39.6	38.6	76.0	80.0	14.9	13.4	-0.1	0.7
27. Chile seco/ancho (Dried Chile)	12	15.2	35.0	30.3	55.0	7.3	12.4	-0.5	6.3
28. Chile seco/guajillo (Dried Chile)	12	17.4	38.3	35.6	49.2	9.6	11.2	-0.6	8.5
29. Chile seco/pasilla (Dried Chile)	12	13.6	32.5	28.0	49.2	10.6	9.2	-2.2	3.6
30. Elote (Corn)	15	43.6	39.3	88.5	79.3	11.5	12.5	1.0	1.3
31. Col (Cabbage)	15	38.2	52.0	76.4	71.3	15.2	13.0	2.0	8.0
32. Pepino (Cucumber)	12	43.2	45.8	81.8	81.7	17.6	15.6	2.3	4.5
33. Calabacita (Squash)	13	45.5	50.0	93.0	88.5	16.0	18.2	0.2	7.0
34. Chicharo (Green pea)	15	41.2	60.0	91.5	88.0	15.9	13.7	-0.7	6.8
35. Miel de abeja (Honey)	10	12.7	46.0	20.9	52.0	4.9	14.4	1.3	11.2
36. Cafe soluble (Instant coffee)[1,5,10]	11	66.1	69.1	69.4	75.5	7.3	5.2	6.9	4.4
37. Ajo (Garlic)	13	36.4	43.1	60.8	69.2	10.4	9.2	1.3	3.0
38. Cerveza (Beer)	14	20.8	28.6	28.6	35.0	7.2	5.8	2.1	3.8
39. Ron (Rum)	11	36.4	71.8	46.3	76.4	5.1	6.7	3.0	6.3
40. Brandy (Brandy)	13	35.0	63.8	39.2	70.0	3.1	5.8	2.0	5.0
41. Vino de mesa/blanco (White wine)	11	14.0	46.4	17.4	47.3	8.9	6.3	5.4	6.0
42. Vino de mesa/tinto (Red wine)	12	20.5	51.7	26.5	52.5	6.4	5.2	3.3	5.1
43. Tequila (Tequila)	10	27.3	57.0	32.7	61.0	3.7	5.6	1.7	5.1
44. Chayote (Chayote)	14	40.6	44.7	89.1	86.0	12.9	21.6	-0.9	4.8
Mean	13	28.2	50.0	49.3	66.0	8.8	10.4	1.2	6.1

Note: Monthly averages of frequencies and magnitudes for each year in percentage. Goods with superscripts 1, 5 and 10 indicate that the null hypothesis of common mean relative prices across firms selling the same good is not significantly rejected at 1, 5, and 10% levels, respectively. For goods without subscripts, the same hypothesis is significantly rejected at 1% level.

Table 1
Inflation Rate in Mexico: 1994 and 1995

Data	1994 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	1994 Total
CPI	0.78	0.51	0.51	0.49	0.48	0.50	0.44	0.47	0.71	0.52	0.53	0.88	7.05
44 goods	—	-4.16	-1.93	1.59	1.70	-0.37	-0.17	-0.25	2.99	3.28	0.90	-0.69	2.93
Data	**1995 Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**1995 Total**
CPI	3.76	4.24	5.90	7.97	4.18	3.17	2.04	1.66	2.07	2.06	2.47	3.26	51.97
44 goods	5.86	6.78	3.06	8.16	7.52	3.89	0.78	-1.50	0.79	4.26	1.59*	1.59*	51.53

Notes: Monthly inflation rate in percentages. Good-specific monthly inflation rates from our sample equal the geometric average over firm-specific inflation rates of firms selling a given good; monthly inflation rates equal the geometric average over good-specific inflation rates. Numbers with asterisks are converted from a two-month inflation rate due to missing observations in 1995:11.

Table 2
Panel regression of price adjustment frequencies and magnitudes

	Dependent variable			
	Frequency of		Magnitude of	
	price increase (F_{jt}^{+})	price change (F_{jt})	price increase (M_{jt}^{+})	price change (M_{jt})
Constant	28.16***	49.26***	8.76***	1.19***
	(1.02)	(0.76)	(0.29)	(0.42)
D_t	21.84***	16.79***	1.64***	4.96***
	(1.71)	(1.38)	(0.47)	(0.62)
Sample size				
	924	924	815	884

Note: Numbers in parentheses are heteroskedasticity and autocorrelation robust standard errors. Sample periods are 1994:2 to 1995:10. Coefficients significant at 1% levels are denoted by ***.

Table 3
Panel regression of price dispersion measures

Dispersion measures (dependent var.)	Mean of dependent var. 1994	1995	Regressor (1) D_t	(2) π_t
(A) Deviation from regime-invariant, firm-specific mean relative price				
MSD_{jt}	11.45	13.98	2.530***	0.179*
			(0.433)	(0.104)
MAD_{jt}	9.76	12.23	2.473***	0.172*
			(0.418)	(0.102)
R_{jt}	27.70	30.21	2.510***	0.421***
			(0.696)	(0.160)
IPR_{jt}	16.16	17.93	1.764***	0.218**
			(0.433)	(0.107)
(B) Deviation from regime-specific, firm-specific mean relative price				
MSD_{jt}	8.77	10.91	2.134***	0.374***
			(0.339)	(0.081)
MAD_{jt}	7.16	9.53	2.376***	0.409***
			(0.325)	(0.079)
R_{jt}	23.91	23.30	-0.612	0.171
			(0.618)	(0.142)
IPR_{jt}	12.98	14.00	1.023**	0.266***
			(0.399)	(0.101)

Note: MSD_{jt}: Mean squared deviation (from firm-specific mean relative price); MAD_{jt}: Mean absolute deviation; R_{jt}: Range of deviation; IPR_{jt}: 10-90th interpercentile range of deviation. Numbers in parentheses are heteroskedasticity and autocorrelation robust standard errors. Sample periods are 1994:1 to 1995:10. Coefficients significant at 1%, 5% and 10% levels are denoted by ***, ** and *, respectively.

Table 4
Panel regression of cross-firm price dispersion measures

Dispersion measure (dependent var.)	Mean of dependent var. 1994	1995	Regressor (1) D_t	(2) π_t	(3) π_{jt}
CV_{jt}	14.66	13.28	-1.387***	-0.199***	0.001
			(0.217)	(0.057)	(0.018)
$\widetilde{R}_{jt}$	49.75	44.25	-5.500***	-0.802***	-0.023
			(0.860)	(0.218)	(0.074)
$\widetilde{IPR}_{jt}$	28.22	26.23	-1.986***	-0.285**	0.028
			(0.492)	(0.130)	(0.041)

Note: CV_{jt}: coefficient of variation; $\widetilde{R}_{jt}$: Range (normalized); $\widetilde{IPR}_{jt}$: 10-90th interpercentile range (normalized). Numbers in parentheses are heteroskedasticity and autocorrelation robust standard errors. Sample periods are 1994:1 to 1995:10 (1994:2 to 1995:10 for (3)). Coefficients significant at 1%, 5% and 10% levels are denoted by ***, ** and *, respectively.