NBER WORKING PAPER SERIES

IMPERFECT INFORMATION AND STAGGERED PRICE SETTINGS

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Working Paper No. 2201

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
April 1987

We are grateful for many helpful suggestions from Olivier Blanchard, Larry Jones, David Romer, Julio Rotemberg, Matthew Shapiro, Michael Whinston, and seminar participants at Columbia, North Carolina State, Ohio State, and the Federal Reserve Bank of Kansas City. The research reported here is part of the NBER's research program in Financial Markets and Monetary Economics. Any opinions expressed are those of the authors and not those of the National Bureau of Economic Research.

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ABSTRACT

Many Keynesian macroeconomic models are based on the assumption that firms change prices at different times. This paper presents an explanation for this "staggered" price setting. We develop a model in which firms have imperfect knowledge of the current state of the economy and gain information by observing the prices set by others. This gives each firm an incentive to set its price shortly after as many firms as possible. Staggering can be the equilibrium outcome. In addition, the information gains can make staggering socially optimal even though it increases aggregate fluctuations.

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I. INTRODUCTION

In many Keynesian models of the business cycle, firms change prices at different times. Even if individual prices change frequently, this "staggered" price setting leads to inertia in the aggregate price level, which causes nominal disturbances to have large and long lasting real effects (see Blanchard[1983, 1986] and Taylor[1980]). A frequent criticism of this research is that the timing of price changes is treated as exogenous. The models show that staggering has important macroeconomic effects, but they do not explain why staggering occurs. In fact, if the firms in these models are allowed to choose when to change prices, all firms change them simultaneously.[1]

This paper attempts to strengthen the foundations of Keynesian models by presenting an explanation for staggered price setting. We develop a model in which firms have imperfect knowledge of the current state of the economy and gain information by observing the prices set by others. This gives each firm an incentive to set its price shortly after as many firms as possible. Staggering can be the equilibrium outcome.[2]

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[1]The result that synchronization is the equilibrium timing is apparently a longstanding folk theorem. It is demonstrated formally for the Blanchard model in this paper and in Ball and Romer (1986).

[2]Other explanations for staggering are presented by Fethke and Policano (1984, 1986), Maskin and Tirole (1985), Parkin (1986), and Ball and Romer (1986). One prominent informal explanation is that firms change prices at different times simply because they face different shocks and different costs of price adjustment. If this were the entire explanation, however, a large enough nominal shock would cause all prices to adjust immediately. Only moderate shocks would have real effects.

The argument that imperfect information can lead to staggered price setting is an old one. Okun(1981), for example, argues that firms' concern for relative wages combined with their ignorance of each others' plans leads to staggering. Okun describes a hypothetical economy in which all firms set wages on January 1 of each year. He then speculates:

> "[T]he inability of firms to assess relative wage prospects would destabilize the synchronized situation. Every employer would like to make a decision in full light of decisions that others had made, but would also like to respond promptly. So an employer would want to move a bit behind the schedule followed by the others. As a result, some employer would decide to shift the wage adjustment date to February 1, in order to observe what all the other employers had done. Others would also want to make such a move, but obviously everyone cannot exercise the preference to bat last. The likely result of this 'time-location' problem is analogous to that of some spatial location problems. It generates a tendency to spread the distribution of wage-adjustment dates around the calendar." (p. 95)

While Okun discusses wages, his point applies equally well to price setting in general. Similar discussions of imperfect information and staggering appear in recent macroeconomics textbooks (for example, Hall and Taylor[1986], Ch. 14).

Despite their popularity, these explanations for staggering have never been formalized. This paper shows that adding imperfect information to Blanchard's(1986) model of monopolistically competitive price setters can create endogenous staggering. In our model, each firm's profit-maximizing price depends separately on a local and an aggregate demand shock, but the firm observes only the sum. If all firms change prices at the same times, each faces Lucas's(1973) signal extraction problem. But when price decisions are staggered, a price setter observes prices set recently by other firms. These reveal the previous price setters' estimates of aggregate demand, which can be used to improve the current firm's estimate.

We use the model to address two questions. First, when does imperfect information lead to staggering? We characterize the conditions under which staggering and synchronization are stable Nash equilibria. Second, can staggering be socially optimal? When information considerations are absent, staggering is Pareto inferior to synchronization because it leads to price level inertia, which exacerbates business cycles. But in the presence of both local and aggregate shocks, staggered price setting helps firms set prices closer to profit maximizing levels and may lead to a net improvement in welfare.

The remainder of the paper consists of four sections. Section II describes a simple version of the model in which local demand shocks are uncorrelated across firms. The following section shows that staggering may be socially optimal in this model, but that it is <u>never</u> a stable Nash equilibrium. Section IV presents a modification of the model in which the economy is composed of a large number of "neighborhoods," each containing a small number of firms.[3] A neighborhood can be interpreted as an industry or geographic area. Local shocks are correlated across firms within a neighborhood, so firms learn more by observing prices set by their neighbors than by observing prices set by others. In this version of the model, staggering <u>can</u> be a stable equilibrium. Finally, Section V discusses generalizations of our results and offers conclusions.

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[3]This is in contrast to Fethke and Policano, who show how staggering may arise in an economy with a small number of large sectors.

Our results illustrate the complementarity of new classical and new Keynesian macroeconomic models. Lucas's framework of imperfect information provides a foundation for Blanchard's model of staggered price-setting. At the same time, the possibility of staggering makes more plausible the idea that information imperfections are an important source of aggregate fluctuations. In actual economies, these imperfections appear short-lived. For example, data on the U.S. price level is available with approximately a one month lag. Short information lags can lead to staggering, however, and staggering causes nominal shocks to have long-lasting real effects.

II. THE SIMPLE MODEL

Our model is an extension of Blanchard's (see the version in Blanchard and Fischer, 1985). The economy contains a large number of firms that produce and sell differentiated products. Each firm fixes its nominal price for two periods. Departing from previous work, we assume that each firm chooses the timing of its price changes; that is, it chooses whether to set its price in even or odd numbered periods. In addition, a firm faces two shocks, a monetary shock and an idiosyncratic real shock. Thus the model can be interpreted as a generalization of Lucas(1973) to the case of imperfect competition.[4]

Omitting constants and writing all variables in logs, the demand for firm

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[4]The assumption that prices are fixed for two periods captures the idea that shocks arrive more frequently than prices are changed. In the concluding section, we discuss the implications of assuming that prices are fixed for more than two periods, or of setting the model in continuous time.

i's product at time t is given by

(2.1) $y_{it} = (m_t - p_t) - \varepsilon(p_{it} - p_t) + u_{it}$, $\varepsilon > 1$,

where y_i is firm i's output, m is the money stock, p is the aggregate price level, p_i is firm i's price, ε is the elasticity of demand, and u_i is a firm-specific demand shock. According to (2.1), a firm's demand depends on three variables: real money, which determines aggregate demand; the firm's relative price; and the local shock. The aggregate price level is defined by

$$p_t = \frac{1}{N} \sum_i p_{it} ,$$

where N is the number of firms. Finally, firm i's cost function is

(2.2) $c_{it} = \gamma y_{it}$, $\gamma > 1$,

where c_i is the log of firm i's costs and γ measures the returns to scale.[5]

Both the money stock and local demand are stochastic. m_t follows a random walk and u_{it} is white noise:

(2.3) $m_t = m_{t-1} + \delta_t$, $\delta_t \sim N(0, \sigma_m^2)$;

(2.4) $u_{it} \sim N(0, \sigma_u^2)$.

The local and aggregate shocks are uncorrelated. In addition, the local shock is uncorrelated across firms. (This will be changed in the "neighborhood"

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[5]Equations (2.1) and (2.2) can be derived from assumptions about tastes and technology in a model of yeoman farmers who use their own labor to produce differentiated goods, and who consume each others' products (see Ball and Romer[1987] and Blanchard and Kiyotaki[1985]). In the yeoman farmer model, (2.2) is the log of farmer i's utility loss from supplying the labor to produce output y_i, and γ measures the degree of increasing marginal disutility of labor. A farmer's total utility is given by the formula for a firm's profits in this paper. The local demand shocks, u_i, can be generated by adding taste shocks to farmers' utility functions. Finally, the formula for the aggregate price level in this paper is a first order approximation of the formula in the yeoman farmer model.

model of Section IV.)[6]

If firm i set its price every period with full knowledge of the shocks, it would choose the price that maximizes profits. In logs, this price is

$$(2.5) \quad p^*_{it} = v(m_t + u_{it}) + (1-v)p_t \quad , \text{ where } \quad v = \frac{\gamma-1}{1+\gamma\varepsilon-\varepsilon} .$$

We assume, however, that the firm fixes its price for two periods. Let x_{it} be the log of the price that firm i sets for t and t+1. In choosing x_{it}, the firm uses all information available at the end of t-1. Ignoring discounting, the firm minimizes the loss function

$$(2.6) \quad L_i = E^i_{t-1}\{(x_{it} - p^*_{it})^2 + (x_{it} - p^*_{it+1})^2\},$$

where E^i_{t-1} is the expectation conditional on information available to firm i at the end of t-1. According to (2.6), the firm minimizes the expected squared deviations of its price from the profit-maximizing level. Because demand is log-linear, $(x_{it}-p^*_{it})^2$ is proportional to $(y_{it}-y^*_{it})^2$, the squared deviation of output from the profit-maximizing level.[7] Minimization of (2.6) implies the simple price setting rule

$$(2.7) \quad x_{it} = (1/2)\ \{E^i_{t-1}p^*_{it} + E^i_{t-1}p^*_{it+1}\} .$$

The crucial departure of our model from previous work is the information structure. Firms observe each others' prices when they are set, but the local demand shocks and the money stock -- which should be interpreted as nominal

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[6]Our qualitative results would not change if we introduced additional disturbances, such as cost shocks, or if we assumed that m and u follow more complicated stochastic processes.

[7]Minimizing (2.6) is equivalent to maximizing a second order approximation to expected profits (see Parkin).

aggregate demand -- are observed with a lag. It is easier to collect other firms' prices than to infer demand, which requires knowledge of others' sales.

Specifically, the government collects information on output and the money stock and publishes it with a two period lag. Firms set x_{it} after observing announcements at t-1, so they have full information about conditions two periods earlier, at t-3. Assuming that the money stock is announced with a two period lag, rather than a longer one, simplifies the analysis but is not crucial. As will be clear below, a shorter lag would eliminate the information gains from staggering, which are the focus of the paper.[8]

It is useful to describe in detail the information available to a firm when it sets x_{it}. While shocks are observed only through t-3, the firm sees all prices through t-1, and therefore observes the aggregate price level through t-1. The demand equation, (2.1), shows that the firm can infer the sum of the aggregate shock and its local shock, $(m+u_i)$, from its own price and sales and the aggregate price level. Since the firm always knows its own price and sales, the composite signal $(m+u_i)$ is observed through t-1.

If price setting is synchronized, this completely describes the information that firm i uses to set x_{it}. But if price setting is staggered, prices set at t-1 reveal further information. As shown below, prices set at t-1 depend on $(m_{t-2}+u_{it-2})$; thus the average of a large number of them reveals m_{t-2}. This is the information gain from staggering. (Under synchronization,

[8]In the United States, the money stock is announced with a very short lag. But if we interpret m_t as nominal aggregate demand (money times velocity), it is realistic to assume a significant lag.

firms observe the prices in effect at t-1, but these were set at t-2 based on information about t-3. Since m_{t-3} is announced, the prices reveal nothing new.)

III. ANALYSIS OF THE SIMPLE MODEL

A. Overview

This section studies the economy described in Section II. We focus on two price setting regimes: synchronization, in which all firms set prices in even periods; and uniform staggering, in which half set prices in even periods and half in odd periods. First, we describe the price setting problem facing a firm in each regime to make clear the information gain from staggering. Then the model is solved for the path of an individual firm's price, x_{it}, and the aggregate price level, p_t. As in previous work, staggered price setting leads to price level inertia. We use the solutions for x_{it} and p_t to compute firms' expected losses in the two regimes. This allows a welfare comparison.

The welfare analysis does not resolve whether firms in a decentralized economy synchronize or stagger their price setting. Therefore, we go on to determine when each regime is a stable Nash equilibrium by asking whether an individual firm has an incentive to change its timing.

The algebra required to derive our results is complicated and generally uninteresting. Therefore, the details of most calculations are relegated to an Appendix that is available from the authors.

B. The Information Gain from Staggering

The Synchronized Regime: If all firms change prices at t, (t+2) and so on, the aggregate price level does not change in alternate periods. This means that $p_t = p_{t+1}$ and $E^i_{t-1}p_t = E^i_{t-1}p_{t+1}$. Since the money stock is a random walk, $E^i_{t-1}m_{t+1} = E^i_{t-1}m_t = E^i_{t-1}m_{t-1}$. Combining these results with firm i's price setting rule, (2.7), and the formula for the profit-maximizing price, (2.5), leads to

(3.1) $x^S_{it} = vE^i_{t-1}m_{t-1} + (1-v)E^i_{t-1}p_t$,

where x^S_{it} is firm i's price in the synchronized regime.

Equation (3.1) shows that x^S_{it} depends on firm i's estimates of m_{t-1} and p_t. Since m_{t-3} is announced, estimation of m_{t-1} reduces to estimation of the last two innovations in the money stock, $(m_{t-1}-m_{t-3}) = (\delta_{t-1}+\delta_{t-2})$. As noted in the previous section, firm i infers two relevant pieces of information, $(m_{t-2}+u_{it-2})$ and $(m_{t-1}+u_{it-1})$, from its sales at t-2 and t-1. Along with m_{t-3}, the two signals reveal $(\delta_{t-2}+u_{it-2})$ and $(\delta_{t-1}+\delta_{t-2}+u_{it-1})$. When price changes are synchronized, the firm has no additional information. In particular, the most recent prices of other firms were set at the beginning of t-2; thus they reveal only information about t-3, which has been announced by the government.

The expectation of $(\delta_{t-1}+\delta_{t-2})$ conditional on $(\delta_{t-1}+\delta_{t-2}+u_{it-1})$ and $(\delta_{t-2}+u_{it-2})$ is given by the simple projection equation

(3.2) $E^i_{t-1}[\delta_{t-1}+\delta_{t-2}] = a_1(\delta_{t-1}+\delta_{t-2}+u_{it-1})+a_2(\delta_{t-2}+u_{it-2})$

where

$$a_1 = \frac{\sigma_m^2+2\sigma_u^2}{\sigma_m^2+3\sigma_u^2+(\sigma_u^2)^2/\sigma_m^2}$$

and

$$a_2 = \frac{\sigma_u^2}{\sigma_m^2+3\sigma_u^2+(\sigma_u^2)^2/\sigma_m^2} .$$

The expectation of m_{t-1} follows immediately:

$$(3.3)\quad E_{t-1}^i m_{t-1} = m_{t-3} + a_1(\delta_{t-1}+\delta_{t-2}+u_{it-1}) + a_2(\delta_{t-2}+u_{it-2}) .$$

According to (3.3), expected money depends on the last announced money stock, m_{t-3}, and the noisy information about recent changes in money. Part C of this section uses (3.3) to solve for the aggregate price level. But first, we compute the expectation of the money stock when price setting is staggered.

The Uniformly Staggered Regime: When half of the firms change prices in each period, p_t does not equal p_{t+1}. Instead of (3.3), the price setting equation implied by (2.5) and (2.7) is

$$(3.4)\quad x_{it}^U = vE_{t-1}^i m_{t-1} + (\tfrac{1-v}{2})(E_{t-1}^i p_t + E_{t-1}^i p_{t+1}) ,$$

where x_{it}^U is firm i's price in the uniformly staggered regime.

Once again, a firm's price depends on its estimate of m_{t-1}. Crucially, this estimate is better under staggering than under synchronization. We show that firms in the staggered regime infer m_{t-2} from prices set at t-1. Thus the only unknown part of m_{t-1} is δ_{t-1}. In the synchronized regime, m_{t-2} is unknown because no prices are set at t-1.

Formally, we assume that staggered firms observe m_{t-2} and then verify this after solving for the price level. It turns out that each price set at t-1 is a linear combination of prices set at t-2 and shocks at t-2 and t-3. Since the local shocks are uncorrelated across firms, they average to zero. Thus the average of prices set at t-1 depends only on prices at t-2 and the money stock at t-2 and t-3. When firm i sets x^U_{it}, it knows prices at t-2 and the money stock at t-3 (which has been announced). Therefore, the average of prices set at t-1 reveals the money stock at t-2.

Since firms know m_{t-2}, estimation of m_{t-1} reduces to estimation of δ_{t-1}. The only relevant information is $(\delta_{t-1}+u_{it-1})$, which a firm infers from its sales at t-1. Projection of δ_{t-1} onto this signal yields

(3.5) $E^i_{t-1}m_{t-1} = m_{t-2} + b(\delta_{t-1}+u_{it-1})$, where $b = \sigma^2_m/(\sigma^2_m+\sigma^2_u)$.

Not surprisingly, (3.3) and (3.5) imply that the error in estimating m_{t-1} has a smaller variance under staggering than under synchronization. This is the information gain from staggering.

C. The Aggregate Price Level

Synchronization: Let x^S_t be the average across firms of x^S_{it}. When all prices are set at t (even), x^S_t is the aggregate price level at t and t+1. To solve for x^S_t, substitute the estimate of m_{t-1}, (3.3), into the expression for x_{it}, (3.1). Applying the method of undetermined coefficients and aggregating (which eliminates the local shocks) leads to

(3.6) $p^S_t = x^S_t = m_{t-3} + \pi_1\delta_{t-1} + \pi_2\delta_{t-2}$ (t even),

where

$$\pi_1 = \frac{va_1[1-(1-v)a_1]+va_2(1-v)(a_1+a_2)}{[1-(1-v)a_1][1-(1-v)(a_1-a_2)] - [a_2(1-v)]^2} ,$$

and

$$\pi_2 = \frac{v(a_1+a_2)+(1-v)a_2\pi_1}{1-(1-v)a_1} .$$

Uniform Staggering: In the staggered regime, half the prices in effect at t are set at t and half are set at t-1. Thus the aggregate price level is

(3.7) $p_t^U = (1/2)\ (x_t^U + x_{t-1}^U)$,

where x_t^U is the average of prices set at t. Substituting (3.7) and (3.5) into (3.4) and applying the method of undetermined coefficients yields[9]

(3.8) $x_t^U = \lambda_0 x_{t-1}^U + \lambda_1 m_{t-1} + (1-\lambda_0-\lambda_1)m_{t-2}$,

where

$$\lambda_0 = \frac{1-\sqrt{v}}{1+\sqrt{v}} \text{ and } \lambda_1 = \frac{[4v+(1-v)(1-\lambda_0)]b}{4-b(1-v)(2+\lambda_0)}; \quad \lambda_0,\ \lambda_1>0, \quad \lambda_0+\lambda_1\leq 1 .$$

Combining (3.7) and (3.8) yields the solution for the aggregate price level:

(3.9) $p_t^U = \lambda_0 p_{t-1}^U + (1/2)\{\lambda_1 m_{t-1} + (1-\lambda_0)m_{t-2} + (1-\lambda_0-\lambda_1)m_{t-3}\}$.

Equation (3.9) shows that staggering leads to price level inertia -- that is, to slow adjustment of the price level to shocks. The degree of inertia depends on λ_0. Perhaps surprisingly, it is independent of the variances of local and aggregate shocks. Inertia is greatest (λ_0 is largest) when v is small. In turn, v is small when demand is elastic so ε is large, or when γ, the returns to scale parameter, is close to 1.

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[9]There are two solutions for x_t^U. We choose the stable one, $0<\lambda_0<1$. Note that x_{t-1}^U depends on x_{t-2}^U, m_{t-2}, and m_{t-3}. Since a firm setting x_t^U observes x_{t-2}^U and m_{t-3}, this verifies our claim that the firm can infer m_{t-2} from x_{t-1}^U.

D. The Optimal Timing of Price Changes

This section compares a firm's loss under synchronization, L^S, to its loss under staggering, L^U, to determine which regime is socially optimal. To calculate each loss, substitute the solutions for a firm's price, x_{it}, the aggregate price level, p_t, and the profit-maximizing price, p^*_{it}, into the loss function, (2.6).[10]

Synchronization is socially optimal when $L^S<L^U$. One can show that the relative sizes of L^S and L^U depend on two parameters: $\rho=\sigma_u/\sigma_m$, the ratio of the standard deviations of the two shocks; and v. Numerical calculations determine the locus of (v,ρ) pairs for which $L^S=L^U$. This is plotted as the lower line in Figure 1. Below the line, $L^S<L^U$, so synchronization is optimal. Above the line, staggering is optimal.

To understand this result, recall that staggering has both benefits and costs. The benefit is improved information. There are two costs: price level inertia, which exacerbates fluctuations in real aggregate demand; and the unintended movements in relative prices that occur when some prices adjust while others are fixed. Since there are both advantages and disadvantages, it is not surprising that staggering is optimal for some parameter values but not for others.

Figure 1 shows that synchronization is optimal when either v or ρ is small. v is small when product demand is highly elastic (ε is large).

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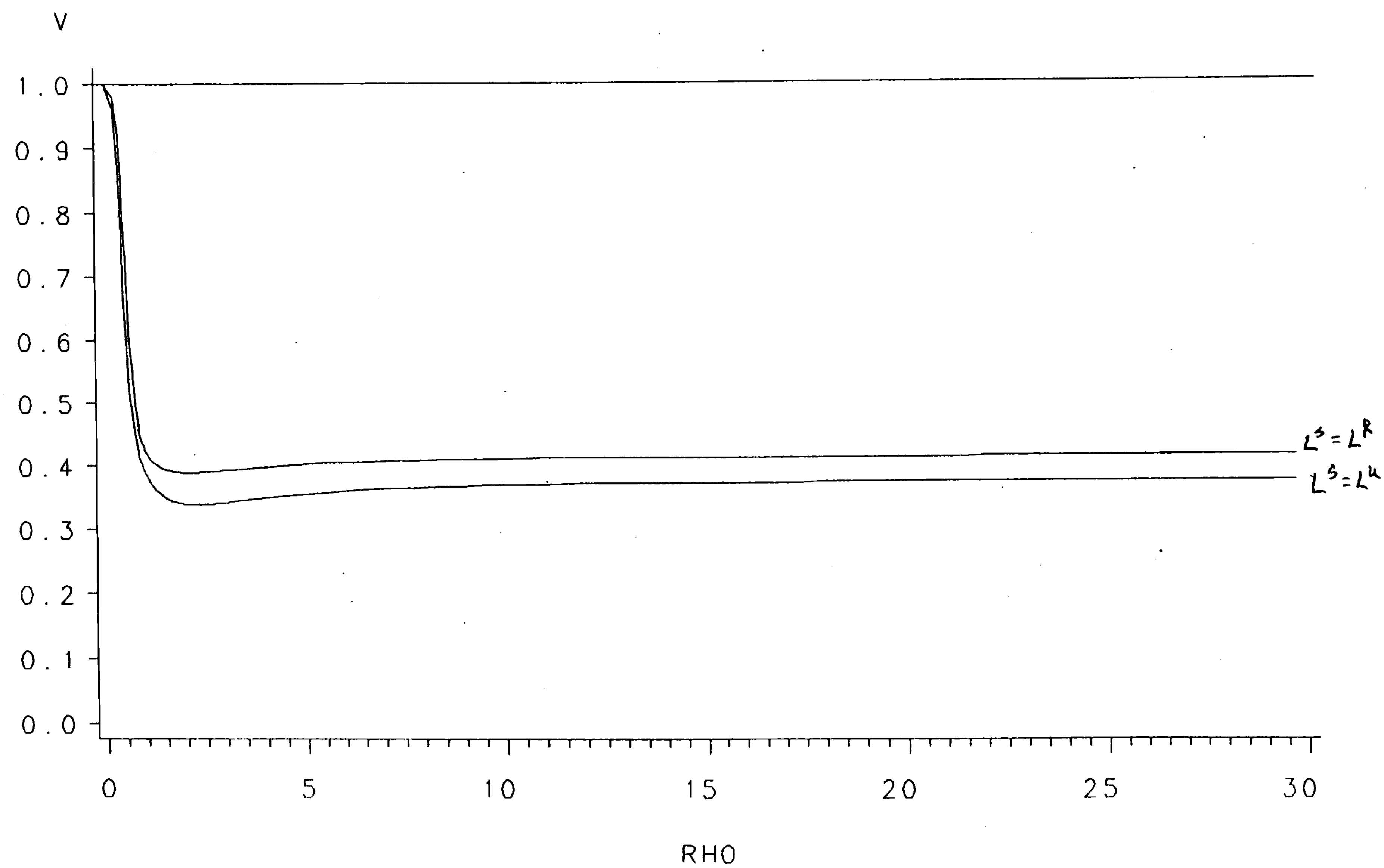
[10]The Appendix contains the expressions for the two losses along with derivations.

Figure 1

SIMPLE MODEL



Elastic product demand implies that the fluctuations in relative prices caused by staggering are very costly. In addition, firms reduce these costly fluctuations by setting prices close to those set in the previous period; thus staggering leads to a high degree of inertia and large fluctuations in aggregate demand. These large costs imply that staggering is undesirable despite the information gains.[11]

Turning to the role of ρ, note that if $\rho=0$, so there are no local shocks, then synchronization is optimal. This special case is essentially the Blanchard model. Information is perfect, and so there is no information gain from staggering. On the other hand, as long as ρ is greater than one, its value is unimportant.[12]

E. Equilibrium

While it is interesting to compare welfare under synchronization and staggering, it is also important to ask when each will arise in a decentralized economy. Therefore, we now assume that each firm chooses whether to change its price in even or odd periods. This allows us to determine when synchronization and staggering are stable Nash equilibria.

Synchronization: If all firms set prices in even periods, can a single "rebel" gain by moving to odd periods? If not, then synchronization is a Nash equilibrium.

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[11] v is also small when γ is close to one -- that is, when the cost function is almost linear.

[12] According to Figure 1, the effect of ρ on the relative sizes of L^S and L^U is not monotonic. We have no explanation for this result.

The rebel sets its price at t and t+2 (odd), while all other firms set prices at t-1 and t+1 (even). Since the economy is large, the rebel's behavior does not affect the aggregate price level. Only the rebel changes price at t, so $p_t^S=p_{t-1}^S$. Using (3.6),

(3.10) $p_t^S = p_{t-1}^S = m_{t-4} + \pi_1\delta_{t-2} + \pi_2\delta_{t-3}$ (t odd).

All firms but the rebel change prices at t+1, so

(3.11) $p_{t+1}^S = m_{t-2} + \pi_1\delta_t + \pi_2\delta_{t-1}$ (t odd) .

Like a firm in the staggered regime, the rebel infers m_{t-2} from prices set at t-1. To see this, note from (3.10) that p_{t-1}^S is a combination of m_{t-4}, m_{t-3}, and m_{t-2}. When the rebel sets its price, m_{t-4} and m_{t-3} have been announced, so p_{t-1}^S reveals m_{t-2}. The rebel estimates the monetary shock at t-1 from the noisy signal $(\delta_{t-1}+u_{it-1})$. Thus the expectation of m_{t-1} is again given by (3.5).

These results lead to solutions for the rebel's price, x_{it}^R, and its loss, L^R. Synchronization is an equilibrium if $L^R>L^S$ -- that is, if the rebel loses by breaking from synchronization.[13] The upper line in Figure 1 shows the (v,ρ) combinations for which $L^R=L^S$. Below this line, synchronization is an equilibrium; above the line, it is not.

The explanation for this result is that there are both costs and benefits to rebelling. The rebel gains information by observing prices set recently by all other firms. On the other hand, breaking from synchronization leads to large fluctuations in the rebel's relative price. If either v or ρ is small

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[13]More precisely, synchronization is an equilibrium if $L^R\geq L^S$, but it is a stable equilibrium only if $L^R>L^S$.

(so either relative price fluctuations have large costs or the information gains from staggering are small), no one chooses to break from synchronization.

Figure 1 shows that for parameter values between the two lines, synchronization is socially optimal but not a Nash equilibrium. In this region, the cost to a rebel of changing its price alone is greater than the cost to a firm in the staggered regime of changing its price with half the other firms. As a result, firms in the staggered regime are better off than firms in the synchronized regime, but no firm is willing to pay the large cost of breaking from synchronization.

Uniform Staggering: Clearly, uniform staggering is a Nash equilibrium for all parameter values. The losses of even and odd period price setters are the same and do not change if a single firm switches cohorts. Therefore, no firm can gain by switching.

In this simple model, however, the staggered equilibrium is never stable. Stability of staggering is defined as follows: after a small perturbation in the cohort sizes away from half and half, firms in the larger group can gain by moving to the smaller one, restoring the equal sizes. To see whether this condition is met, we study the behavior of the economy when the cohorts have arbitrary sizes. We compute a firm's loss as a function of the proportion of firms in its cohort, k. The derivative of this function at $k=1/2$ is always negative. Thus, following a perturbation away from uniform staggering, firms in the larger cohort are better off than firms in the smaller one. All firms want to join the larger group, and so uniform staggering is unstable.[14]

This result arises because each firm wants to minimize fluctuations in its relative price, and therefore wants to synchronize its price-setting with as many firms as possible. Crucially, this incentive to join the larger cohort is not offset by any information loss. When a firm in the large cohort sets its price, it observes prices set in the previous period by 50-% of the firms; a firm in the small cohort observes prices set by 50+% of the firms. Because the economy is large, the two sets of prices reveal the same information. Specifically, when either set is averaged, the local shocks that affect individual prices average to zero, and the same aggregate information (m_{t-2}) is revealed.

The earlier parts of this section show that staggering may be socially optimal. The stability result implies, however, that we have not explained why staggering occurs in a decentralized economy. Fortunately, this result is not robust. The next section presents a plausible modification of the model that provides an incentive for firms to join the smaller of two cohorts. This leads to stable equilibria with uniform staggering.

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[14]One can show that no regime other than synchronization or uniform staggering (that is, no value of k besides 1/2 and 1) is ever an equilibrium. Thus the model possesses no stable equilibrium for parameter values above the upper line in Figure 1.

IV. THE NEIGHBORHOOD MODEL

A. Motivation

In the previous section, uniform staggering is unstable because each firm wants to join the larger of two price-setting cohorts. There are several ways to reverse this result. One approach is to assume that gathering price data is costly. Suppose that the cost of observing enough prices set at t-1 to obtain a good estimate of m_{t-2} increases as the (t-1) cohort shrinks. (For example, firms might need to travel farther to reach a given number of t-1 price setters.) This is an incentive for each firm to set its price after the larger cohort -- that is, to join the smaller cohort.[15]

Another approach, and the one adopted here, is to note that a firm cares more about prices in its industry or geographic area than about prices in the rest of the economy. It is easy to see why a firm learns more from prices in its "neighborhood." If neighboring firms are direct competitors, then a firm's demand depends heavily on its neighbors' prices. In addition, if demand shocks are correlated within a locality or industry, neighbors' prices provide information about neighborhood demand.

If neighborhoods are small, then firms have an incentive to join the smaller of two price-setting cohorts. In the model without neighborhoods, the

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[15]Alternatively, one could assume that a firm observes only a small subset of other firms' prices. In this case, the firm obtains an imperfect estimate of x_{t-1}. When the prices observed by the firm include many set at t-1, the estimate of x_{t-1} is more precise, and therefore provides more information about m_{t-2}. This is an incentive for the firm to join the smaller cohort.

cohorts have the same information as long as both are large in absolute terms. But in a neighborhood of ten firms (for example), six prices reveal more than four. Thus each firm has an incentive to change its price after as many neighbors as possible.

We formalize these ideas by assuming that local demand shocks are correlated across neighboring firms. Part B of this section describes this modification of the simple model. The remainder of the section addresses the same questions as Section III: When are synchronization and staggering socially optimal, and when is each a stable equilibrium?

B. Revision of the Model

Assume that each firm belongs to a neighborhood of n firms, where n is a small number. The economy contains a large number of neighborhoods. Part of the local demand shock, u_{it}, is common to firms within a neighborhood. Therefore, a firm learns about its shock by observing neighbors' prices. Formally, if firm i is a member of neighborhood I, then

(4.1) $u_{it} = \theta_{It} + \theta_{It-1} + \eta_{it}$.

θ_I is common to firms within a neighborhood but uncorrelated across neighborhoods, while η_i is uncorrelated across all firms. θ and η are both white noise with mean zero and variances σ_θ^2 and σ_η^2.

Persistence of the neighborhood shock is crucial. We show that neighbors' prices set at t-1 contain information about θ_{It-2}. According to (4.1), θ_{It-2} is part of u_{it-1}; thus neighbors' prices help a firm disentangle u_{it-1} and m_{t-1}. If u were not serially correlated, the information about θ_{It-2} in neighbors' prices would not be useful for estimating t-1 shocks.

Aside from the composition of u_{it}, the model is the same as in Sections II and III. In particular, we retain the simplifying assumption that complete information is available with a two period lag. Thus firms setting x_{it} at the end of t-1 observe m, θ_I, and η_i for t-3 and earlier.[16]

C. Optimality and the Stability of Synchronization

This section studies the optimal timing of price changes and the conditions under which synchronization is a Nash equilibrium. In other words, the two lines in Figure 1 are recomputed for the neighborhood model. In comparing regimes, we define uniform staggering as an equal split of each neighborhood into odd and even period price setters.[17] The results and their derivations are similar to the ones for the simple model. Therefore, we sketch the analysis here (the Appendix contains details).

The information gain from staggering is greater in the current model than in the simple model. Once again, m_{t-2} is revealed by the average of all prices set at t-1. The additional information comes from neighborhood prices. Each price set by a neighbor of firm i at t-1, x_{jt-1}, reveals $(\theta_{It-2}+\eta_{jt-2})$, the sum at t-2 of the neighborhood shock and the neighbor's idiosyncratic shock. Firm i also infers $(\theta_{It-2}+\eta_{it-2})$, the t-2 sum of the neighborhood

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[16]When t-3 shocks are known, x_{it} depends on information about t-1, t-2, and t-3. In contrast, if some shocks were never revealed, firms would estimate current shocks using information from all previous periods. As a result, prices would depend on shocks from t-1 back to t-∞.

[17]This is not the only reasonable definition. We could also study regimes in which half of all firms belong to each cohort but not every neighborhood is divided equally. However, one can show that no type of staggering besides an equal split of each neighborhood can be a stable equilibrium.

shock and its <u>own</u> idiosyncratic shock, from its t-2 sales. When firm i averages this information over the t-1 price setters and itself (a total of (n/2)+1 observations), it obtains $(\theta_{It-2}+\bar{\eta}_{it-2})$, where $\bar{\eta}_i$ is the average of the η_j's and η_i.

In the simple model, firm i estimates δ_{t-1} from $(\delta_{t-1}+u_{it-1})$. In the current model, firm i uses both $(\delta_{t-1}+u_{it-1})$ and $(\theta_{It-2}+\bar{\eta}_{it-2})$, and this leads to better estimates. Intuitively, $(\theta_{It-2}+\bar{\eta}_{it-2})$ is a noisy signal of θ_{It-2}, which is part of u_{it-1}. Thus observing $(\theta_{It-2}+\bar{\eta}_{it-2})$ helps firm i disentangle u_{it-1} and δ_{t-1}. Since the information gains from staggering are greater in this model than in the simple one, the ranges of parameter values over which staggering is socially optimal and over which synchronization is <u>not</u> an equilibrium are somewhat larger. That is, both lines in Figure 1 move down.

Presentation of the results is complicated by the addition of two parameters: n, the size of the neighborhood; and $\alpha=\sigma_\theta^2/\sigma_\eta^2$, the relative importance of neighborhood and firm-specific shocks. For comparability with Figure 1, we fix n and α and graph the results in (v,ρ) space.

Figure 2 presents results for $\alpha=1$ and n=10. Below the lowest line, synchronization is Pareto superior to uniform staggering. Below the middle line, synchronization is an equilibrium. Figure 3 shows the consequences of varying α and n. These parameters do not affect the qualitative results.

<u>D. The Stability of Uniform Staggering</u>

The important departure of the neighborhood model from the simple model of Section III is that uniform staggering is a stable Nash equilibrium for some

Figure 2

ALPHA = 1, NEIGHBORHOOD SIZE = 10

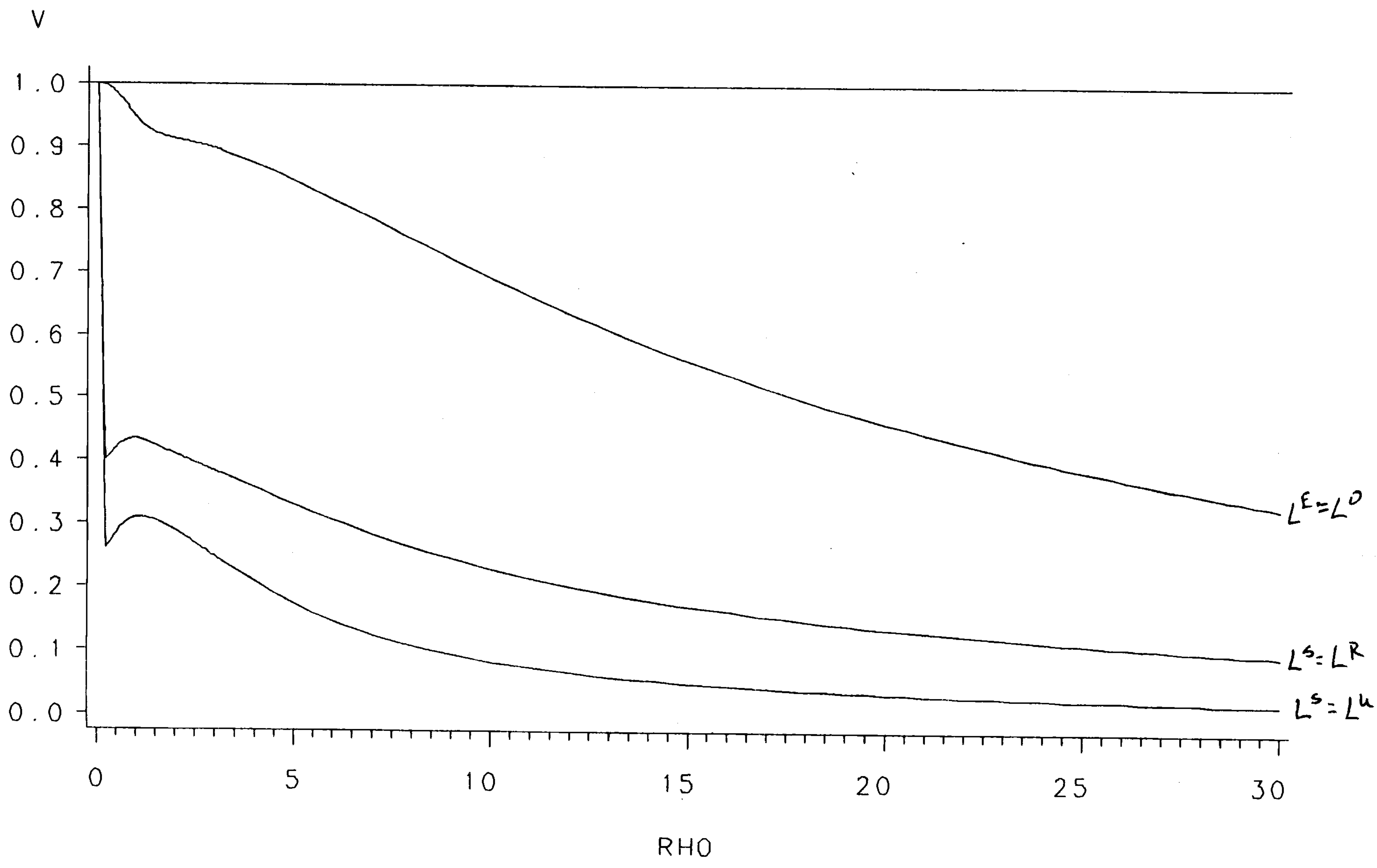
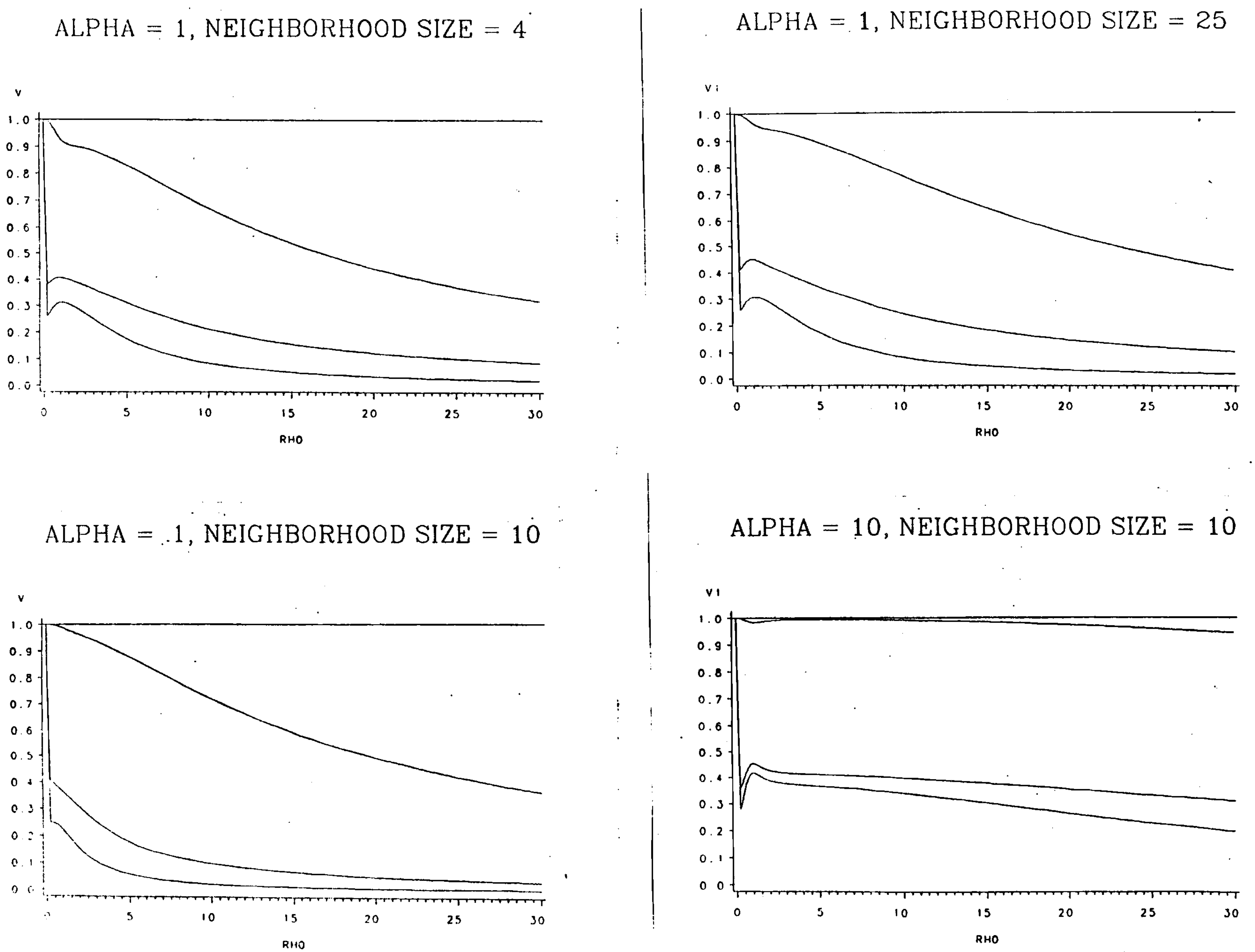


Figure 3



ALPHA = 1, NEIGHBORHOOD SIZE = 4
V
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
RHO
ALPHA = 1, NEIGHBORHOOD SIZE = 25
VI
ALPHA = .1, NEIGHBORHOOD SIZE = 10
ALPHA = 10, NEIGHBORHOOD SIZE = 10

parameter values. As in the simple model, staggering is always an equilibrium, and so we focus on the question of stability.[18] Stability is defined as follows. Suppose that one firm in each neighborhood is moved from the odd to the even cohort, so that $(\frac{n}{2}+1)$ firms in each neighborhood set prices in even periods and $(\frac{n}{2}-1)$ set them in odd periods. Uniform staggering is stable if firms in the larger cohort have greater losses than firms in the smaller cohort.[19]

Let L^E and L^O be the losses of firms in the even (larger) and odd (smaller) cohorts. In Figures 2 and 3, the top line shows the parameter values for which $L^E=L^O$. Above this line, uniform staggering is stable; below the line, it is not.

Staggering can be stable because firms in the smaller of two cohorts have

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[18]The equilibrium question is more subtle than in the simple model. Uniform staggering is a Nash equilibrium if no firm has an incentive to move from one of its neighborhood's cohorts to the other, given that all other neighborhoods remain equally divided. One can show that a firm that switches loses information because it synchronizes its price setting with more of its neighbors. There is no offsetting gain, because the firm still changes prices with 50% of the economy, and therefore experiences the same fluctuations in its relative price. No firm wants to switch, and so staggering is an equilibrium.

[19]There are other reasonable definitions of stability based on different perturbations. For example, we could move one firm in a single neighborhood from the odd to the even cohort while leaving the other neighborhoods unchanged and compare the losses of the two cohorts in the perturbed neighborhood. By this weak definition, the condition for stability is the same as the condition for staggering to be a Nash equilibrium, and it always holds (see the previous footnote). Alternatively, we could perturb a small but non-negligible proportion of the neighborhoods while leaving the others unchanged. With this definition, we conjecture that staggering is stable for a wider range of parameter values than in the text.

better information. A firm setting its price at t observes prices set at t-1. These reveal $(\theta_{It-2}+\bar{\eta}_{it-2})$, where again $\bar{\eta}_i$ is the average of η over firm i and all neighbors setting prices at t-1. A firm in the smaller cohort observes more prices set at t-1, and therefore $\bar{\eta}_{it-2}$ has a smaller variance. $(\theta_{It-2}+\bar{\eta}_{it-2})$ is a better estimate of θ_{It-2}, and so it is more useful in disentangling local and aggregate shocks. For some parameter values, this information advantage outweighs the disadvantage of changing prices at the same time as less than half the firms.

It is crucial that the neighborhoods are small. A firm that observes six neighboring prices set at t-1 obtains a better estimate of θ_{It-2} than a firm that observes four. In contrast, if the neighborhoods were large, a firm observing prices set by 50%+ of its neighborhood would learn no more than a firm observing 50-%. The η_{jt-2}'s would average to zero for both cohorts, and so all firms would observe θ_{It-2} exactly.

Figure 2 shows that staggering is stable for large values of v. Again, if v is small, then product demand is highly elastic and relative price variation is very costly. In this situation, firms want to synchronize price-setting with as much of the economy as possible by joining the large cohort.

Staggering is also stable when ρ is large -- that is, when local shocks are large relative to monetary shocks. As ρ approaches infinity, the lines in Figures 2 and 3 approach the horizontal axis, which means that staggering is stable (and socially optimal) for all v. As Lucas (1977) emphasizes, aggregate shocks are responsible for only a small part of the uncertainty facing firms in actual economies. Thus it seems realistic to assume that ρ

is large, and hence that staggering is stable for a wide range of v.

A large ρ leads to staggering because small monetary shocks imply a stable aggregate price level. When the price level is stable, a firm's relative price does not fluctuate much even if many other prices adjust while the firm's price is fixed. Thus there is little cost to joining the smaller of two cohorts. But the benefit does not disappear. Even if monetary shocks are unimportant, firms want to distinguish neighborhood shocks from firm-specific shocks, and so they value the greater information of the small group. All firms want to join the small cohort, and so staggering is stable.[20]

E. Comparison of Equilibrium and Optimum

As in the simple model, the conditions under which synchronization and staggering are stable equilibria differ from the conditions under which they are socially optimal. For parameter values between the two lower lines in Figures 2 and 3, synchronization is an equilibrium even though staggering is optimal. In addition, between the top and bottom lines, staggering is optimal but not a stable equilibrium. According to these results, the incentives for an individual firm to break from synchronization or to join the smaller of two cohorts are weaker than the incentives for a social planner to choose staggering. Furthermore, for parameter values between the two upper lines, there is no stable equilibrium.

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[20]Figure 3 shows that changes in n and α have little effect on the stability of staggering. There is one exception: for α=.1, staggering is stable only for a narrow range of v. When α is small, neighborhood shocks are small compared to firm-specific shocks; thus the model is close to the model without neighborhoods, in which staggering is never stable.

The relative positions of the three lines in Figures 2 and 3 do not appear robust. To take an example discussed above, suppose that gathering price data is costly. Let c(k) be the cost of inferring m_{t-2} from prices set at t-1, where k is the proportion of the economy in a firm's cohort. Assume that c'(k)>0: the cost of gathering price data rises as a firm's cohort grows and the t-1 cohort shrinks. To see the implications for the positions of the lines, recall that the bottom line is determined by comparing L^S to L^U, and the middle line by comparing L^S to L^R. This means that the relation between the two lower lines depends on L^U and L^R. The cost of gathering prices under uniform staggering is c(.5), while the cost to the rebel is c(0), because no other firm belongs to the rebel's cohort. Since c(.5) is greater than c(0), introducing the cost raises L^U more than it raises L^R. One can show that this raises the bottom line relative to the middle line, and that the two may switch positions. By a similar argument, the top line may move below the others. (The position of the top line depends on c'(.5), which affects the benefit from belonging to the small cohort after a perturbation away from uniform staggering.)[21]

V. CONCLUSION

Imperfect information can lead to staggered price setting. While fluctuations in relative prices are minimized when firms make decisions at the same times, a firm gains valuable information about aggregate demand if it

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[21]We also suspect that changing assumptions about the timing of announcements or the stochastic processes followed by shocks could change the relative positions of the lines.

waits to see other prices. This information gain can lead firms to break from synchronization and can make staggering a stable equilibrium. Thus staggered price adjustment, a crucial foundation of new Keynesian macroeconomic models, can arise from rational economic behavior.

Imperfect information can also make staggering socially optimal. Staggering leads to price level inertia, which exacerbates aggregate fluctuations. However, by helping firms set prices closer to full information levels, staggering creates efficiency gains that may outweigh the costs. Policy proposals to reduce staggering -- for example, by requiring labor unions to sign contracts at the same times -- could reduce welfare despite lessening inertia.

The model predicts that staggering is least likely when firms are nearly perfectly competitive and when idiosyncratic shocks are small. If the model is applied to an industry rather than the entire economy, these predictions are borne out by casual observation. In the automobile industry, products are fairly close substitutes and shocks are likely to affect all firms equally. The result is the synchronized pricing that we see. On the other hand, the drug store on the corner and the diner next door produce goods that are poor substitutes, and they are likely to face different shocks. Thus it is not surprising that they change prices at different times.

This paper has studied a very specific model. Some results, notably the relation between the equilibrium and optimal regimes, are not likely to be robust. We doubt, however, that reasonable changes in the model would reverse the conclusion that staggering can be both optimal and a stable equilibrium if firms possess strong market power or idiosyncratic shocks are large.

A natural extension of our analysis is to relax the assumption that prices are fixed for two periods. If prices are fixed for longer, one can show that the incentive for a rebel to break from synchronization is greater. Thus the region of parameter values for which synchronization is an equilibrium is smaller. Intuitively, if prices are set for many periods, then a rebel setting its price one period after other firms is only slightly out of step. The cost in relative price fluctuations is small, while the rebel still gains the information in others' prices. Unfortunately, it is very difficult to determine how changing the frequency of price adjustment affects the socially optimal regime and the stability of uniform staggering.

Our intuition about the costs and benefits of staggering carries over to continuous time, but the model must be modified. In this paper, firms have perfect information about prices set in the most recent period. In a continuous time model, it would be unrealistic to assume that firms observe and respond to others' prices the instant they are set.[22] Instead, one might assume that firms learn about prices slowly, gaining full information after a discrete amount of time (e.g., the time it takes to visit all neighboring stores). This modification of the model would complicate the analysis considerably.

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[22] For example, given the length of labor contract negotiations, one union's wage can influence another's only if the first union signs its contract significantly earlier.

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