A Dynamic Model of Oligopoly and Oligopsony in the U.S. Potato-Processing Industry

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ABSTRACT

In this paper, we estimate oligopoly and oligopsony price distortions in the U.S. potato chips and frozen French fries sectors, based on a linear-quadratic, multi-period optimization model of processors that face quadratic adjustment costs associated with a change in the processed quantity of input. Based on this model, we are able to derive a parameter that nests various types of firm conduct, ranging from price taking through Nash-Cournot behavior to collusion. In addition, we estimate market conduct and associated price distortions in a sub-game perfect, dynamic-feedback model, and compare the results with those derived from an open-loop model. The results indicate that the behavior of potato-processing firms is much closer to price taking than to collusion. Moreover, we find that price distortions due to oligopsony in the purchase of potatoes are smaller than oligopoly price distortions in either the potato chips or the frozen French fries sectors. [EconLit citations: L13, Q13.] © 2005 Wiley Periodicals, Inc.

1. INTRODUCTION

Studies of food industry market structure typically suggest that many food markets are not perfectly competitive (Bhuyan & Lopez, 1997; Sexton, 2000; Sexton & Lavoie, 2001). The food-processing industries often involve relatively few processors who purchase a raw farm product from many local producers, transform it into a final product and sell to a large number of consumers. Therefore, food processors often exert oligopsony power in their input markets and exert oligopoly power in their output markets.

Several studies in the so-called "new empirical industrial organization" (NEIO) consider static models of oligopsony and oligopoly applied to the food-processing and

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agricultural sectors (Schroeter, 1988; Schroeter & Azzam, 1990; Wann and Sexton, 1992). The standard theoretical criticism of these, and other studies in the field, is that they attempt to model dynamic interactions between agents, namely, reactions to each other's quantity or price strategies in a static framework, using the concept of conjectural variations (Dockner, 1992). The typical defense of the methodology has been to argue that in empirical analysis, conjectural variations parameters are a means of indexing the degree of market power exercised in a specific sector as opposed to being an explicit behavioral parameter, i.e., they measure the wedge between output (input) prices and marginal cost (marginal revenue product) (Karp and Perloff, 1993a; Sexton, 2000; Sexton and Zhang, 2001).[1]

Irrespective of how one interprets conjectural variations, it is surprising that empirical analysis of market power has not moved more in the direction of explicitly capturing dynamic behavior, especially in light of the fact that perhaps the most important advance made in the field of industrial organization has been the ability to analyze multi-period games that have oligopolistic equilibria. In particular, it has been shown that non-cooperative collusive equilibria can be obtained in repeated games (Fudenberg & Tirole, 1989). This is reinforced by a recent survey of the empirical industrial organization literature by Slade (1995) that suggests that static one-shot Nash games in either quantities or prices are nearly always rejected by the data.

Karp and Perloff (1993a, 1993b), Slade (1995), and Williams and Isham (1999) have also argued that the use of static models is appropriate only if the processing industry can adjust quickly. Usually, food processors cannot costlessly and instantly vary the quantity of input that they process. To account for large adjustment costs in either storage and capital accumulation or production, Karp and Perloff (1989, 1993c), and Deodhar and Sheldon (1996) consider a dynamic model of oligopoly. Karp and Perloff (1989, 1993c) found that the rice and coffee export markets are oligopolistic, but they are closer to competitive than collusive. Deodhar and Sheldon (1996) found that, the German banana import market is not competitive rather firms operate in a Nash-Cournot fashion. A criticism of these studies, however, is that they focus only on oligopoly power and ignore modeling oligopsony power. Sexton (2000) argues that models that focus only on oligopoly or oligopsony run the risk of understating the extent of the market-power distortion and/or erroneously attributing the distortions to the wrong form of market power.

In this study, we use a model that allows us to derive indices for both oligopsony and oligopoly price distortions in a dynamic setting. In particular, we extend the model initially developed by Karp and Perloff (1993a, 1993b) to account for oligopsony.[2] We also allow for different conjectural elasticities in both the input and output market, and also calculate separate price distortion indices. We develop a linear-quadratic, multi-period optimization model of processors that face quadratic adjustment costs associated with a change in the processed quantity of input. From the model, we are able to derive a parameter that nests various types of firm conduct, ranging from price taking, through Nash-Cournot behavior to collusion. In addition, we appeal to two important equilibrium concepts: the first, based on open-loop strategies, where each firm chooses their future

[1]An additional criticism of this methodology has recently been put forward by Corts (1998). He shows that with high seasonality in demand, it may be incorrect to make inferences about market power based on a conjectural variations approach.

[2]Other examples of dynamic empirical games in the literature include Roberts and Samuelson (1988) (cigarettes), and Hall (1990) (titanium dioxide).

path of processing levels in the initial period; the second, based on feedback strategies, where firms choose processing levels as a function of the state variables. Our objective is to estimate market conduct and associated price distortions in a sub-game perfect, dynamic feedback model, and to compare the results with those derived from an open-loop model.

The model is applied to the U.S. potato-processing sector, with the focus being on two of the most important processed products, frozen French fries and potato chips, which account for 29 and 11%, respectively, of potato processing. Both sectors have market structures dominated by a few large firms. In the frozen-potato sector, which is dominated by frozen French fries production, the four-firm concentration ratio is reported to be 80% (U.S. International Trade Commission, 1997), with only five major firms in the sector, Lamb-Weston, R.J. Simplot, McCain Foods, Ore-Ida, and Nestle-Carnation (Richards, Patterson, & Acharya, 2001). The largest firm in this sector is Lamb-Weston, which averaged a market share of 20% over the past 15 years. In addition, a key characteristic of firms in this sector is that they sell predominantly to firms such as McDonalds and Burger King in the food service sector. In the potato chip sector, the four-firm concentration ratio was reported to be 64% in 1996 with a single firm, Frito-Lay, a subsidiary of PepsiCo Inc., which has dominated the industry since the 1970s, accounting for a 50% market share in the late 1990s (Hatirli, 2000).

The stylized facts would suggest that these two processing sectors have the potential to exert market power in both their input and output markets.[3] Interestingly, Richards, Patterson, and Acharya (2001) have recently conducted an analysis of the frozen processed potato product sector in the Pacific Northwest, which accounts for 80% of U.S. frozen potato product output. Drawing on the repeated game, imperfect monitoring model of Green and Porter (1984), they consider a dynamic model of oligopsony where punishment strategies, based on a reversion to Nash, are necessary to sustain a collusive oligopsony in a repeated game context, where punishment is triggered if observed prices reach a certain level.[4] The authors found that potato growers' losses due to oligopsony amount to approximately 1.6% of market revenue per month.

The present study differs from Richards, Patterson, and Acharya (2001) in a key way. The trigger price model adapted by Richards, Patterson, and Acharya is based upon the assumption that firms that defect from the collusive oligopsony/oligopoly equilibrium can be punished through the remaining firms varying quantities. If one firm causes the input/output price to rise/fall, it will be punished by the other firms, who also raise/lower their input/output prices as they revert to the Nash equilibrium quantity in the input/output market. However, this assumes that there are neither capacity constraints nor other costs of adjustment facing firms (Haskell & Martin, 1994). For example, Brock and Scheinkman (1985) have shown that collusion is much easier to sustain when there are no capacity constraints. The dynamics in our model are based on the assumption that

[3]Richards, Patterson, and Acharya (2001) note that, in 1997, the Potato Growers of Idaho filed suit against one of the large processors, alleging pressure was placed on growers to leave the bargaining association. The case subsequently failed as growers were unwilling to testify.

[4]The logic of this model is that with perfect information, one can appeal to the 'folk theorem' result that collusive equilibria can be sustained in a repeated non-cooperative game, where one-period defections are punished through reversion to Nash (Friedman, 1971). If, however supply is random, prices will be an imperfect signal of rivals' behavior, and, therefore, equilibria will vary between Nash and collusion, based on trigger price strategies.

potato-processing firms do face significant costs in adjusting the quantity they process and, hence, may limit the extent to which collusion can be sustained in equilibrium.[5]

The paper is organized as follows. In section 2, a linear-quadratic model is described. The model includes a potato supply equation, potato chips and frozen French fries demand equations, and a Markov adjustment equation that captures interactions among firms. The estimation methods are outlined in section 3. The parameters of the supply, demand, and adjustment equations are used in the solution to a dynamic programming problem in order to derive the market conduct and adjustment parameters. Then in section 4, the potato-processing sector and the data used in our analysis are described. In addition, the results of the econometric analysis are reported and discussed. Finally, in section 5, we conclude with a summary of our results and implications of our analysis.

2. THE DYNAMIC MODEL

The theoretical model developed in this paper describes the behavior of potato-processing firms facing adjustment costs in the quantity they process. The objective is to estimate a dynamic conjectural variations parameter in the context of a linear-quadratic dynamic model.[6] When modeling imperfect competition in a dynamic framework, two equilibrium concepts are commonly used: open loop and feedback Nash equilibrium.[7] In open-loop equilibrium, the strategy of processing firms is to choose a path of input and output quantities in the initial period. Processing firms do not revise this decision in subsequent periods in response to unexpected shocks. Since strategies are not dependent on the current state, and firms are committed to a pre-announced plan, the open-loop model is not sub-game perfect. Strategies are sub-game perfect if they represent a Nash equilibrium in every sub-game of the original game. Committing to strategies at the start of the game is clearly not sub-game perfect, if a processing firm subsequently wants to change strategy in response to rival firms' strategies. In this sense, the open-loop model is the dynamic analog of the static, one-shot Nash equilibrium, where processing firms assume the quantity decisions of their rivals as given.[8]

In feedback equilibrium, processing firms choose input and output levels as a function of the current state variables. Firms revise their decisions each period and choose optimal strategies. As current state variables summarize the latest available information, and since firms take the mechanism for determining future behavior as given, feedback strategies can be referred to as Markov strategies, and feedback equilibrium can be considered sub-

[5]In the case of potato processing, adjustment costs may be important for two key reasons. First, the fact that processors enter into pre-season contracts with potato suppliers means that the ability to adjust quantities upwards will be contingent on any thinness of the spot market. Likewise, contract commitments may make it more costly to adjust quantities downwards. Second, in the case of frozen French fries, processing markets are typically localized, and hence, the ability to change input quantity is spatially constrained, which may impose additional adjustment costs on processing firms.

[6]Riordan (1985) was the first to use the term dynamic conjectural variations.

[7]There are also closed-loop models, where evolution of the state is also included as information in the game.

[8]In an open-loop model, firms simultaneously commit themselves to a time-path of output choices. Due to the fact that firms have only one decision point at the start of the game, then the stationary values of output will be the same as the output choices in a static, one-shot Nash game, (Dockner, 1992, p. 383; Fudenberg & Tirole, 1989, p. 529; Vives, 1999, p. 337–338).

game perfect.[9] It should also be noted that the adjustment paths of the open-loop and feedback equilibrium are identical if firms either collude or act like price takers, whereas two different adjustment paths and steady-state output levels are implied when firms process quantities between the extremes of either price taking or collusion (Karp & Perloff, 1993a, 1993b).

To make the estimation tractable, a linear-quadratic model is considered. The term linear-quadratic comes from optimal control theory and refers to a problem where the objective function is quadratic and the constraints are linear. The linear-quadratic approach has frequently been used in theoretical models of oligopoly (Dockner, 1992; Fershtman & Kamien, 1987; Karp & Perloff, 1993a; Reynolds, 1987). A particular advantage of using this approach is that closed-form solutions can be found for the equilibria of differential games and, therefore, it is possible to solve analytically for the market conduct parameter and the adjustment parameter (Dockner, 1992; Karp & Perloff, 1993a, 1993b; Slade, 1995).[10]

The optimization problem that each potato-processing firm solves is the following. At time t, firm i decides how much to produce in the current period q_{it}, or equivalently, it decides how much to change its production $u_{it} = q_{it} - q_{it-1}$ so that it maximizes its discounted stream of profits

$$\sum_{t=1}^{\infty} \beta^{t-1} \left[p_t k q_{it} - w_t q_{it} - \phi q_{it} - \left(\gamma_i + \frac{\delta}{2} u_{it} \right) u_{it} \right], \tag{1}$$

where p_t is the price received for either potato chips or frozen French fries in period t, w_t is the price paid for potatoes in period t, $(kp_t - w_t - \phi)q_{it}$ is the contemporaneous profit, k is the conversion factor from raw potatoes to either potato chips or frozen French fries, ϕq_{it} are production costs in addition to the cost of purchasing potatoes, ϕ implying constant marginal costs, $(\gamma_i + 0.5\delta u_{it})u_{it}$ is the quadratic cost of adjustment, and β is the discount factor.

We assume that potato chips/frozen French fries are produced with a fixed proportions, single material input (potatoes) technology. Based on data reported on the potato-processing firms' web pages, and also in USDA's (2001) potato summaries, we assume that it takes one pound of raw potatoes to produce either a quarter pound of potato chips or a half-pound of French fries. The assumption of fixed proportions applies particularly well to the potato-processing industry since inputs other than potatoes cannot be substituted in the production of potato chips or frozen French fries.[11]

A linear or a double log representation is usually chosen when estimating retail demand and farm supply functions, (Alston, Sexton, & Zhang, 1997; Sexton & Zhang, 2001). In this paper, linear inverse demand and supply functions are chosen for computational ease.

[9]Nash equilibria in feedback strategies are usually required to be sub-game perfect (Basar & Olsder, 1982). See Slade (1995) for a discussion of the Markov assumption. Note also that the combination of feedback strategies with sub-game perfection is known as Markov perfection.

[10]Essentially, the assumption of a linear quadratic model, with linear constraints and quadratic objective function has the attractive property that there exist optimal feedback strategies that are linear in the state (Slade, 1995; Vives, 1999). Consequently, our choice of this functional form is not based on empirical observation for potato processing, but for analytical tractability, virtually all applications of state-space games having been limited to the linear quadratic approach.

[11]See Sexton (2000), footnote 14, for an excellent discussion of the debate over whether to assume fixed or variable proportions in food-processing technology.

In period t, potato-processing firms face an inverse linear demand curve for the product they produce

$$p_t = a(t) + bkQ_t^i \tag{2}$$

where p_t is the price of either potato chips or frozen French fries in period t, $Q_t^i = q_{it} + q_{jt}$ is the combined usage of potatoes to produce either potato chips or frozen French fries by firm i and its rival firm(s) j in the relevant sector in period t, where I denotes the potato chips or the frozen French fries industry, $a(t)$ includes the effects of exogenous variables, and b is the demand slope. Separate demand functions are estimated: one for the potato chips sector and one for the frozen French fries sector.[12] Potato-processing firms also face an inverse linear supply curve for the potatoes used in the production process:

$$w_t = c(t) + dQ_t, \tag{3}$$

where w_t is the price of fresh potatoes in period t, Q_t is the production of potatoes for all uses in period t, $c(t)$ includes the effects of exogenous variables, and d is the supply slope. Potato production Q_t includes potatoes used in either the potato chips or frozen French fries sector Q_t^I, as well as potatoes used in either other processing sectors or for fresh use Q_t^*, i.e. $Q_t = Q_t^I + Q_t^* = q_{it} + q_{jt} + Q_t^*$.

Substituting the demand and the supply functions (equations (2) and (3)) into the objective function (1) yields the following expression:

$$\sum_{t=1}^{\infty} \beta^{t-1} \Bigg\{ (a + bk(q_{it} + q_{jt}))kq_{it} - [c + d(q_{it} + q_{jt} + Q_t^*)]q_{it} - \phi q_{it} - \left(\gamma_i + \frac{\delta}{2} u_{it}\right) u_{it} \Bigg\}, \tag{4}$$

where a, b, c, and d are the coefficients of the demand and supply equations.

We define a value function $J_i(\boldsymbol{q}_{t-1}; v, v^*)$ as the present value of discounted future profits of firm i, where $\boldsymbol{q}_{t-1} \equiv (q_{1,t-1}, q_{2,t-1})$ is the state vector, $v = \partial q_{jt}/\partial q_{it}$, $i \neq j$, is the market conduct index, which represents a change in the output of the rival firm(s) in response to a change in the output of firm i, and $v^* = \partial Q_t^*/\partial q_{it}$, which represents a change in the output of the other processing sectors and the fresh market in response to a change in the output of firm i. The parameter v reflects the market conduct of a firm with respect to its rivals in the same processing industry, while v^* reflects the market conduct of a firm with respect to other processing industries and the fresh market. The market conduct parameters, reflecting the industry competitiveness, are taken into consideration when firms set their outputs. The control rules v and v^* together with the state vector $\boldsymbol{q}_{t-1}$ determine the dynamic programming equation corresponding to the above objective function:

[12]The demand function also treats both potato chips and frozen French fries as homogeneous goods. Thus, we assume that potato chips and frozen French fries are non-differentiated products. This is a reasonable assumption for frozen French fries, which are largely sold as generic commodities to the food service sector (Richards, Patterson, & Acharya, 2001). It may be less reasonable for potato chips, although the separation of the largest processing firm from the next three largest firms will likely pick up some of the effects of branded products.

$$J_i(\boldsymbol{q}_{t-1}; v, v^*) = \max_{q_{it}} \Bigg[(a + bk(q_{it} + q_{jt}))kq_{it} - (c + d(q_{it} + q_{jt} + Q_t^*))q_{it} - \phi q_{it} - \left(\gamma_i + \frac{\delta}{2} u_{it}\right) u_{it} + \beta J_i(\boldsymbol{q}_t; v, v^*) \Bigg] \quad (5)$$

Here and in subsequent sections, the analysis is simplified to include two players: a firm and an aggregate of its rivals within a potato-processing industry.

3. ESTIMATION METHODS

Our objective is to derive estimates of the market conduct parameter v, the adjustment coefficient, δ and the input and output market price distortions. Firm i's value function $J_i(\boldsymbol{q}_{t-1}; v, v^*)$ in equation (5) is a quadratic function in u_{it}. As a result, the Markov control rules are linear, and the state vector $\boldsymbol{q}_t$ can be written as a linear function of the lagged state vector $\boldsymbol{q}_{t-1}$

$$\boldsymbol{q}_t = \boldsymbol{g}(t) + \mathbf{G}\boldsymbol{q}_{t-1}, \quad (6)$$

where $\boldsymbol{g}(t)$ is a column vector and $\mathbf{G}$ is a 2×2 matrix. This adjustment equation will be estimated, and $\mathbf{G}$ will be used to calculate the market conduct parameter v and the adjustment coefficient, δ. We consider the symmetric case of equal market conduct parameters, v, and equal adjustment coefficients δ for all firms. This assumption implies that $\mathbf{G}$ is symmetric such that $\mathbf{G}_{ii} = g_1$, $\mathbf{G}_{ij} = g_2$ for $i \neq j$.[13] In other words, changes in a firm's processed quantity, with respect to a change in its own lagged quantities, is assumed equal for all firms. Likewise, changes in a firm's processed quantity with respect to a change in the lagged quantities of other firms, is also assumed equal for all firms. In the empirical estimation, we cannot reject this assumption of equal coefficients on lagged own quantity and lagged other firms' quantities. Given the symmetry, the unobservable conduct parameter v can be inferred from the two elements of $\mathbf{G}$, g_1 and g_2, and the assumed value of the discount rate β. Following Karp and Perloff (1993a, 1993b), v and δ in the open-loop case satisfy the following equation:

$$\mathbf{K}_i V_i = [\mathbf{G}^{-1}(\mathbf{I} - \mathbf{G})(\mathbf{I} - \beta\mathbf{G})]' \mathbf{e}_i \delta, \quad (7)$$

where V_i is a 2×1 vector with 1 in the ith position and v in the other position, $\mathbf{I}$ is the identity matrix, $\mathbf{e}_i$ is the ith unit vector, $\mathbf{e}$ is a column vector of 1's, and $K_i = (d + \phi - k^2 b)(\mathbf{e}\mathbf{e}_i' + \mathbf{e}_i\mathbf{e}')$. The solutions to equation (7) are $\delta = (d + \phi - k^2 b)/Z_{21}$, and $v = (Z_{11}/Z_{21}) - 2$, where $\mathbf{Z} = [\mathbf{G}^{-1}(\mathbf{I} - \mathbf{G})(\mathbf{I} - \beta\mathbf{G})]'$. (See appendix A for the explicit derivation.)

[13]Treating firms as having similar conjectures and similar adjustment coefficients is a relatively restrictive assumption, implying that firms have similar cost structures. Unfortunately, as shown by Karp and Perloff (1993b), while the symmetry assumption is unnecessary for deriving equations (7) and (10), it is necessary to make this assumption in order to solve equations (7) and (10).

For the feedback case, following Karp and Perloff (1989), the following two vectors are defined:

$$y_i = [\mathbf{I} - \beta(\mathbf{G}' \otimes \mathbf{G}')]^{-1}[(\mathbf{G}' \otimes \mathbf{G}')(vec(\mathbf{K}_i))], \tag{8}$$

$$x_i = [\mathbf{I} - \beta(\mathbf{G}' \otimes \mathbf{G}')]^{-1}[(\mathbf{G}' \otimes \mathbf{G}') - (\mathbf{I} \otimes \mathbf{G}') - (\mathbf{G}' \otimes \mathbf{I}) + \mathbf{I}][vec(\mathbf{e}_i\mathbf{e}_i')], \tag{9}$$

where the $vec(\cdot)$ operator stacks the columns of a matrix. The vec operation is used to "re-matricize" y_i and x_i to obtain the 2×2 matrices $\mathbf{Y}_i$ and $\mathbf{X}_i$. If firms follow feedback strategies, then v and δ satisfy the following equation (Karp & Perloff, 1993a, 1993b)

$$[\mathbf{K}_i + \beta\mathbf{Y}_i + (\mathbf{e}_i\mathbf{e}_i' + \beta\mathbf{X}_i)\delta_i]v_i = \mathbf{G}'^{-1}\mathbf{e}_i\delta_i. \tag{10}$$

Equations (7) and (10) derived for the case of oligopoly and oligopsony are very similar to the equations derived in Karp and Perloff (1993a, 1993b) for the case of oligopoly. The key difference is that the adjustment parameter in their model depends on the demand slope b, whereas in our model the adjustment parameter depends on both the demand and supply slopes via the term $(d + \phi - k^2b)$. It is interesting to note though that, as in Karp and Perloff (1993c), the demand slope b and the supply slope d do not affect the market conduct parameter v. Therefore, v depends only on how firm i adjusts its quantity with respect to its own lagged and its rival's lagged quantities. The adjustment parameter δ is inferred from $\mathbf{G}$, the demand slope b, the supply slope d, the conversion factor k, and other production costs. Thus, the cost of adjusting the processed quantity depends both on the lagged quantities and on the output demand and input supply functions. Since reliable data on marginal potato-processing costs are not available, we assume that $\phi = 0$.[14] Exclusion of ϕ does not affect the estimates of conjectural variations, as $v = (Z_{11}/Z_{21}) - 2$, is independent of ϕ. The marginal processing cost ϕ does, however, affect the estimate of adjustment costs as $\delta = (d + \phi - k^2b)/Z_{21}$, and our estimates of δ will, therefore, provide a lower bound for the adjustment costs in the potato-processing industries. Similarly to Karp and Perloff (1989, 1993c), we simplify the analysis by assuming that $\gamma_i = 0$.

The first order condition of this problem involves the market conduct parameters v and v^* and the adjustment coefficient δ:

$$p_t k = w_t + (1 + v)(d - bk^2)q_{it} + dv^*q_{it} + \delta u_{it} - \beta\left[\frac{\partial J_i(\boldsymbol{q}_t; v, v^*)}{\partial q_i} + \frac{\partial J_i(\boldsymbol{q}_t; v, v^*)}{\partial q_j}v\right], \tag{11}$$

where $v = \partial q_{jt}/\partial q_{it}$, $i \neq j$, is the market conduct parameter in the output market for either potato chips or frozen French fries, and $v^* = \partial Q_t^*/\partial q_{it}$ represents how much the other processing sectors and the fresh market will change their potato quantities, ∂Q_t^*, in response to a change in firm i's potato quantities, ∂q_{it}. If $v^* > 0$, this implies that market behavior in the potato input market differs from that in the relevant output market. This follows from the fact that, say, frozen French fries (potato chips) processors are competing with other processors and the fresh market for potatoes. In order to evaluate whether

[14]Karp and Perloff (1989) made a similar assumption in their study of the rice export market.

$v^* > 0$, we also include lagged quantities of other processing sectors and the fresh market in the adjustment equations, and test for the significance of the coefficient.[15] In the event that this coefficient is small in magnitude, we would conclude that v^* is zero and, therefore, that the frozen French fries and potato chips industries are relatively competitive with respect to each other.

As noted earlier, in static models, v is often interpreted as a firm's constant conjectural variation about its rival(s), i.e., how firm(s) j will change output (input) in response to a change in firm i's output (input). In the open-loop equilibrium, v can be interpreted in the same way. The values of parameter v lie in a range from -1, for the case of perfect competition, through 0 for Nash-Cournot, to 1 for perfect collusion. In the case of feedback equilibrium, we follow Karp and Perloff (1989), and interpret v as determining the firm's control rule and its value function $J_i(\boldsymbol{q}_{t-1}; v, v^*)$.[16] The values of parameter v fall in the same range as those for open loop equilibrium, such that if $v = -1$ or 1, the feedback and open-loop equilibria are the same, whereas if $v = 0$, the feedback and open-loop Nash-Cournot equilibria are not the same.

The parameters v and v^* determine whether or not potato-processing firms are perfectly competitive, but it is hard to interpret how far from perfect competition either the input or output markets are. In order to develop indices of the extent to which market power is exerted, equation (11) is rewritten as:

$$p_t k(1 + \theta_i^I/\eta) = w_t(1 + \theta_i/\varepsilon) + \delta u_{it} - \beta\left[\frac{\partial J_i(\boldsymbol{q}_t; v, v^*)}{\partial q_i} + \frac{\partial J_i(\boldsymbol{q}_t; v, v^*)}{\partial q_j} v\right]. \qquad (12)$$

Equation (12) is the dynamic analog of the static model presented in Schroeter (1998), and Sexton (2001), where $\theta_i^I = (\partial Q^I/\partial q_i) q_i/Q^I = [\partial(q_i + q_j)/\partial q_i] q_i/Q^I = (1 + v) q_i/Q^I$ is the ith firm's output conjectural elasticity in either the potato chips or frozen French fries market, $\theta_i = (\partial Q/\partial q_i) q_i/Q = [\partial(q_i + q_j + Q^*)/\partial q_i] q_i/Q = (1 + v + v^*) q_i/Q$ is the ith firm's input conjectural elasticity in the potato market, $\eta = (\partial Q^I/\partial p) p/Q^I = (1/bk) p/Q^I$ is the price elasticity of demand for either potato chips or frozen French fries, and $\varepsilon = (\partial Q/\partial w) w/Q = (1/d) w/Q$ is the price elasticity of potato supply. In other words, $\theta_i^I(\theta_i)$ is the ith firm's belief as to how market output (input) will change with respect to their own change in output (input), weighted by the output (input) market share of firm i. Even if $v^* = 0$, the conjectural elasticity in the output market will necessarily be higher than the conjectural elasticity in the input market because the market share of an individual firm is higher in the case of the potato-processing market as compared to the potato input market. The conjectural elasticity measures departures from perfect competition in the output (input) market, and falls in the range, $\theta_i^I(\theta_i) \in [0,1], \theta_i^I(\theta_i) = 0$ for price taking firms, and $\theta_i^I(\theta_i) = 1$ for pure monopoly (monopsony). Values of $\theta_i^I(\theta_i)$ between these extremes reflect varying degrees of oligopoly (oligopsony).

Given estimates of the conjectural elasticities, two useful measures of the degree of exertion of market power in each sector can be developed from equation (12). The well-

[15]As we were unable to get any closed-form solution for v^*, we chose to assess its relevance empirically by inserting the lagged quantities of potatoes used by other processing industries in the adjustment equation.

[16]In subsequent papers, Karp and Perloff (1993a, 1993c) interpret v as a measure of the equilibrium trajectory of the gap between marginal cost and price. This reflects the current practice of not interpreting v as a conjectural variations parameter (Sexton, 2000), which in turn is a reflection of the criticisms conjectural variations models have been subject to in the theoretical literature, e.g., Friedman (1983); Ulph (1983).

known Lerner index measures the monopoly price-cost margin, which, in a static equilibrium, is a function of the inverse price elasticity of demand. This index has been generalized to account for the range of market structures, so that in equilibrium, the inverse price elasticity of demand is adjusted by an index of seller concentration, the Herfindahl index, and a conjectural variations parameter (Cowling & Waterson, 1976).[17]

The Lerner index for firm i, L_i, can be derived by re-arranging equation (12):

$$L_i = \frac{p_t k - w_t(1 + \theta_i/\varepsilon)}{p_t k} = \frac{A}{p_t k} - \frac{\theta_i^I}{\eta}, \tag{13}$$

where the left-hand side of equation (13) is the price-cost margin, and the right-hand side is the static Lerner index, $-\theta_i^I/\eta$, plus the additional term, $A = (\delta u_{it} - \beta[\partial J_i(\boldsymbol{q}_t; v, v^*)/(\partial q_i) + \{(\partial J_i(\boldsymbol{q}_t; v, v^*)/(\partial q_j)\}v])$, where δu_{it} are the costs of output adjustment, and $\beta[.]$ is the discounted shadow value of an extra unit of output. In our empirical analysis, we are unable to observe the term A, consequently, in estimating the static Lerner index, $-\theta_i^I/\eta$ we recognize this will likely be a biased estimate of the price-cost margin.[18]

In addition, the difficulty associated with obtaining firm level data has often led researchers to assume certain aggregation conditions hold when calculating the sector conjectural elasticity, and hence, the sector Lerner index. Specifically, it is typically assumed that all firms have the same market share. An advantage of our study is that the market share of the largest firm can be differentiated from the combined shares of the next three largest firms in the sector. Therefore, in this paper, different conjectural elasticities, θ_i^I, are first estimated for the largest and next largest three firms in the relevant sector, and then, following Porter (1983), we calculate a sector output conjectural elasticity as $\theta^I = \Sigma_i s_i \theta_i^I$, where $s_i = q_i/Q^I$, the output market share of each firm i.[19] From this we are able to calculate a sector Lerner index, $L = -\theta^I/\eta$.

For monopsony power, an analog to the Lerner index is defined as the difference between marginal net revenue product and input price as a proportion of the input price, which, in a static equilibrium, is a function of the inverse price elasticity of input supply. Using equation (12), this index M_i can be written for a single firm i in the input market:

$$M_i = \frac{p_t k(1 + \theta_i^I/\eta) - w_t}{w_t} = \frac{A}{w_t} + \frac{\theta_i}{\varepsilon}, \tag{14}$$

where the left-hand side of equation (14) is the mark-down in the input market, and the right-hand side is made up of the static index, θ_i/ε, plus the additional term A. Conse-

[17]Cowling and Waterson (1976) were the first to provide a theoretical structure for much of the empirical work conducted in the cross-sectional, structure/conduct/performance approach to analyzing the effects of market power.

[18]While Pyndyck (1985) originally noted that the static Lerner index may not be an appropriate measure of market power in dynamic markets, the analysis presented in this paper is closer to that of Hunnicutt and Aadland (2003).

[19]Ignoring monopsony power, the simple, static first-order condition can be written as $(pk - w)/pk = \theta^I/\eta$, where the left-hand side is the price-cost margin, and the right-hand side is as already defined. Given the assumed symmetry of $v_i = v$, and the aggregation condition, $\theta^I = \Sigma_i s_i \theta_i^I$, this can easily be re-written as $(pk - w)/pk = [\Sigma_i s_i^2 (1 + v)]/\eta$, where $\Sigma_i s_i^2$ is the Herfindahl index of seller concentration. This is precisely the definition of the Lerner index originally derived by Cowling and Waterson (1976).

quently, in estimating the static index, θ_i/ε will be a biased measure of the mark-down. Also, as with Lerner index, we calculate a sector index, $M = \theta/\varepsilon$, where the potato input market conjectural elasticity, θ, is the weighted sum of the processing firms' input conjectural elasticities, θ_i, the weights being the input market shares of the firms, $[\theta = \Sigma_i \theta_i (q_i/Q)]$.

4. RESULTS

4.1 The Potato-Processing Industry

Between 1960 and 1999, total U.S. potato production doubled from 257 million cwt in 1960 to 478 million cwt in 1999 (National Agricultural Statistics Service, NASS). The major food uses of potatoes as a percent of total potato production in 1999 included fresh potatoes (28%), frozen French fries (29%), other frozen potato products (5%), potato chips (11%), dehydrated potatoes (11%), and canned potatoes (1%). In contrast, in 1960, potato utilization was fresh potatoes (58%), frozen French fries (5%), potato chips (8%), and dehydrated potatoes (4%). The processing sector has clearly been growing over the past 40 years, utilizing from 23% to 57% of total potato production. Most of the growth in the processing industry has been due to growth in the frozen French fries sector, while the potato chips and dehydrated potatoes sectors show a slight growth. In this paper, we consider the potato chips and the frozen French fries sectors. The dehydrated potato, canned potato, and other frozen potato sectors are not examined due to their small shares of potato utilization, and also a lack of consistent data on prices, and market shares of the largest firms in the respective sectors.

While processed quantities for the largest and the next three largest firms were not available directly, market share data for the potato chips and frozen French fries sectors were obtained from Hatirli (2000). The data include the four-firm concentration ratios and the market share of the largest processing firm in the potato chips (Frito-Lay) and frozen French fries (Lamb-Weston) sectors. The quantities of either potato chips or frozen French fries processed by the largest firm, and the sum of the three next largest firms, are calculated as their market shares multiplied by the utilization of U.S. potatoes as either potato chips or frozen French fries.

Our goal is to examine market conduct and price distortions in the potato chips and the frozen French fries sectors, given that there are costs of adjusting the processed quantity of potatoes. The largest firm in each sector is assumed to engage in a dynamic game with the second, third, and fourth largest firms in the sector. The second, third, and fourth firm market shares are combined and treated as one firm because of lack of detailed and consistent time-series data on the market shares for those firms in either of the sectors. Considering the interaction between the largest firm and the next largest three firms somewhat relaxes the more restrictive assumption commonly made in the literature that all firms in an industry are identical.

4.2 Supply and Demand Equations

One supply equation is estimated for potatoes, and separate demand equations are estimated for potato chips and frozen French fries, respectively, using 2SLS. Instrumental variables are used when the error term is correlated with some of the independent variables in the model in order to ensure that the estimation results are unbiased. In the first estimation step, potato chips, frozen French fries, and potato quantities are regressed on several instrumental variables (all other independent variables except the quantities). In the second step, potato chips, frozen French fries, and potato prices are regressed on the predicted values for the potato chips, frozen French fries, and potato quantities respectively, which were estimated in first step. Farm production data are obtained from the USDA-NASS (2001) potato database for 1960–1999. The database includes U.S. total production of potatoes; utilization of potatoes for potato chips and frozen French fries; potato stocks and potato seed prices; and potato prices. Data on retail prices of potato chips, frozen French fries, and beef are from the Bureau of Labor Statistics, and U.S. Department of Labor. All quantity variables are measured in millions of pounds and all price variables are measured in cents per pound. As noted earlier, we assume that a pound of potatoes produces a half-pound of frozen French fries or a quarter pound of potato chips.

From the supply and demand estimates, only the estimate of the supply slope d, and the demand slopes b are used to estimate the quantity adjustment parameter. The supply and demand equations do not influence the market conduct parameter, which is determined from the interaction among the processing firms rather than from the interaction of the processing firms with the potato growers or potato chips and frozen French fries consumers. The elasticities, however, play an important role in the calculation of the price distortions due to oligopoly and oligopsony.

The results for estimation of the linear inverse potato supply and demand functions are shown in Table 1. The estimated parameters for the potato supply slope and the potato chips and frozen French fries demand slopes are of the expected sign, and are statistically significant at the 5 percent level in the potato chip model, and statistically significant at the 10 percent level in the potato supply and frozen French fries demand models. Income, measured by gross domestic product, has a positive and significant effect on potato chips and French fries prices. Potato seed prices are associated with higher potato prices, while potato stocks are associated with lower potato prices. The positive and significant coefficients on the time trend in the potato chips and French fries equation show that prices have increased over time. The positive and significant coefficient on the time trend squared shows that potato prices have increased over time, with a higher rate in more recent years. On the other hand, potato chips prices have increased over time but with a lower rate in more recent years. The coefficient on the time trend squared was not significant for French fries prices and was dropped from the analysis. The price elasticity of potato supply is 0.66, the price elasticity of demand for potato chips is -1.07, and the price elasticity of demand for frozen French fries is -3.34. Highly price elastic demand may mean that processing firms are somewhat limited in setting high prices as consumers may shift to other substitutes. The relatively elastic supply indicates that processing firms may also be limited in setting low prices to potato growers as growers can also choose to sell their production in the fresh market and avoid contracting with processing firms.

4.3 Adjustment Equations

In addition to the estimated supply and demand slopes, the dynamic model also requires estimation of the Markov equations for the largest and the next three largest firms. The quantities of either potato chips or frozen French fries processed by the largest firm are regressed on its own lagged quantities and the sum of the lagged quantities of the other three largest firms in the sector. Similarly, the sum of the quantities processed by the

TABLE 1. Supply of Potatoes and Demand for Potato Chips and Frozen French Fries

Variable	Estimate	t ratio
Supply of Potatoes		
Constant	0.0078	0.10
Potato Quantity	0.0085	1.41**
Potato Stocks	−0.0204	−2.21*
Potato Seed Price	1.4857	4.63*
Time	0.0026	1.04
Time Squared	0.0002	3.42*
Elasticity of Potato Supply	0.6558	
Adjusted R^2	0.9523	
Demand for Potato Chips		
Constant	0.9321	3.13*
Potato Chips Quantity	−0.9113	−4.28*
Income	0.0013	5.16*
Time	0.1237	10.84*
Time Squared	−0.0076	−5.31*
Elasticity of Potato Chips Demand	−1.0678	
Adjusted R^2	0.9790	
Demand for Frozen French Fries		
Constant	0.2539	9.45*
Frozen French Fries Quantity	−0.0442	−1.65**
Income	0.0001	4.98*
Beef Price	0.0011	0.62
Time	0.0131	2.70*
Elasticity of French Fries Demand	−3.3410	
Adjusted R^2	0.9565	

Notes. * Significant at the 5% level; ** significant at the 10% level. Elasticities are calculated at the data means.

second, third, and fourth largest firms in the sector are regressed on their lagged quantities and the lagged quantities of the largest firm in the sector.

As noted before, the **G** matrix gives a relationship between the current processed quantities $\boldsymbol{q}_t$ and the lagged quantities $\boldsymbol{q}_{t-1}$, given by $\boldsymbol{q}_t = \boldsymbol{g}(t) + \mathbf{G}\boldsymbol{q}_{t-1}$. The **G** matrix in the adjustment equation is estimated using Zellner's seemingly unrelated equations method using the SAS software. The estimation requires a cross-equation symmetry restriction that the coefficients on the own lagged quantities are equal ($\mathbf{G}_{11} = \mathbf{G}_{22} = \mathbf{G}_1$) and that the coefficients on the other firm's quantities are equal ($\mathbf{G}_{21} = \mathbf{G}_{12} = \mathbf{G}_2$). The F statistic for imposing these restrictions and the restriction that the coefficients on the time trend are equal shows that the restrictions cannot be rejected. Therefore, the restrictions are imposed in the estimation and the regression results are shown in Table 2.

The results show that the system is stable since $-1 < \mathbf{G}_1 + \mathbf{G}_2 < 1$ and $-1 < \mathbf{G}_1 - \mathbf{G}_2 < 1$. The coefficients on own lagged quantities are 0.61 for the potato chips industry and 0.83 for the frozen French fries industry. The coefficients on the other firm's quantities are −0.31 for potato chips and −0.14 for frozen French fries. These coefficients are used to calculate the market conduct parameters v. To test whether the market conduct

TABLE 2. Adjustment Equations: Regression of Quantities on Lagged Quantities

	Potato Chips Sector		Frozen French Fries Sector	
	Largest Firm	Next Three Largest Firms	Largest Firm	Next Three Largest Firms
Constant	0.3108 (4.56*)	0.2603 (3.77*)	0.3187 (3.23*)	0.4131 (3.50*)
Time	0.0236 (4.22*)	0.0236 (4.22*)	0.0275 (2.21*)	0.0275 (2.21*)
Lagged Quantities for Largest Firm	0.6116 (6.67*)	−0.3046 (−3.30*)	0.8287 (13.15*)	−0.1381 (−2.20*)
Lagged Quantities for Next Three Largest Firms	−0.3046 (−3.30*)	0.6116 (6.67*)	−0.1381 (−2.20*)	0.8287 (13.15*)
Adjusted R^2	0.9520	0.3970	0.9250	0.9597
Durbin's h	−1.56	1.80	0.5828	−0.8461

Notes. Numbers in parentheses are t statistics; * significant at 5% level.

parameter with respect to the other processing industry and the fresh potato market, v^*, is zero, we insert the lagged quantities of potatoes utilized in other sectors in the adjustment equations. The coefficients on the lagged quantities of other potato utilizations are small in magnitude (−0.01 for the potato chips sector and −0.08 for the frozen French fries sector) and are not statistically significant. We conclude, therefore, that the quantity of a processing firm is mainly determined by its own lagged quantity and the lagged quantity of other firms in the sector and is not influenced by quantities used in either other processing sectors or the fresh market.

4.4 Market Conduct and Adjustment Parameters

Using the estimates of the demand and supply slope parameters and the adjustment matrix **G**, and assuming that the discount factor $\beta = 0.95$, the market conduct parameters v and the adjustment coefficients δ are estimated for both open loop (o) and the feedback (fb) versions of the model. The results shown in Table 3 satisfy the theoretical inequalities that the market conduct parameters v lie between price taking and collusion, $-1 < v^{\omega} < 1$, where $\omega = o$ or ft, and that the adjustment parameters in each of the models is positive, $\delta^{\omega} > 0$.

For the potato chips sector, the market conduct parameter $v^o = -0.9851$ in the open-loop case, and $v^{ft} = -0.9463$ in the feedback case. For the frozen French fries sector, the market conduct parameter $v^o = -0.9629$ in the open-loop case, and $v^{ft} = -0.8815$ in the feedback case. The open-loop model parameters of market conduct are slightly closer to price taking than the feedback model parameters.

Standard errors for v are calculated based on the delta method.[20] The delta method expands a function of a random variable around its true parameter vector, usually with a first-order Taylor series approximation, and then takes the variance of the expression.

[20]While v is a univariate function of **G**, δ is a multivariate function of G, b, and d, hence, the Taylor approximations and numerical derivatives are complex in this case.

TABLE 3. Market Conduct, Adjustment, and Price Distortion Parameters

Parameters	Potato Sector	Potato Chips Sector	Frozen French Fries Sector
Open loop model			
Market conduct parameter v^{o}		-0.9851	-0.9629
		(0.042)	(0.325)
Adjustment parameter δ^{o}		0.1071	0.0858
Largest firm's conjectural elasticity θ_i^o		0.0042	0.0108
Sector conjectural elasticity θ^o	0.00056	0.0021	0.0114
Largest firm's price distortion index L_i^o		0.0039	0.0018
Sector price distortion index (M^o and L^o)	0.00085	0.0020	0.0034
M^o and L^o with 3% discount rate	0.00068	0.0017	0.0027
Feedback model			
Market conduct parameter v^f		-0.9463	-0.8815
		(0.092)	(0.325)
Adjustment parameter δ^f		0.1086	0.0890
Largest firm's conjectural elasticity θ_i^f		0.0151	0.0345
Sector conjectural elasticity θ^f	0.00181	0.0077	0.0364
Largest firm's price distortion index L_i^f		0.0142	0.0056
Sector price distortion index (M^f and L^f)	0.00276	0.0072	0.0109
M^f and L^f with 3% discount rate	0.00253	0.0068	0.0100

Note. Numbers in parentheses are standard errors based on a Taylor approximation.

Denote as $\mathbf{G}^e$ the coefficient estimates of the matrix $\mathbf{G}$ from the adjustment equations. Since the market conduct parameter v is a function of the $\mathbf{G}$ matrix in the adjustment equations, the first-order Taylor series approximation implies that:

$$v(\mathbf{G}) = v(\mathbf{G}^e) + (\mathbf{G} - \mathbf{G}^e)v'(\mathbf{G}^e). \tag{15}$$

The variance of the market conduct parameter v is equal to the variance of the right-hand side of equation (15) and involves expressions of the variance of the $\mathbf{G}$ matrix (calculated in the adjustment equations) together with the numerical derivative of v with respect to $\mathbf{G}$:

$$\text{var}[v(\mathbf{G})] = \text{var}(\mathbf{G})[v'(\mathbf{G}^e)]^2. \tag{16}$$

Based on t-statistic tests, the price-taking hypothesis of $v = -1$ cannot be rejected, but the Nash-Cournot hypothesis of $v = 0$ is rejected. Therefore, the behavior of potato-processing firms is close to price taking but not to collusion. These results are based only on the way firms adjust their quantities, given their own, and their rivals' lagged quantities.

As expected, the adjustment coefficients δ are higher in the feedback than the open-loop version of the model. In other words, since the adjustment costs are higher in the feedback than in the open-loop models, firms are more reluctant to adjust the quantities of processed potatoes over time.

4.5 Price Distortion Indices

The conjectural elasticities, $\theta^I(\theta)$, are estimated using the market conduct parameters, v, for the two sectors. Table 3 shows that these estimates are not much larger than zero in either output sector, for the open loop (feedback) case, the relevant value is 0.0021 (0.0077) for potato chips, and 0.0114 (0.0364) for frozen French fries. For the largest firm in each output sector, the estimates of the conjectural elasticities are also small, in the open loop (feedback) case the value being 0.0042 (0.0151) for potato chips, and 0.0108 (0.0345) for frozen French fries. Finally, in the case of the input market, the conjectural elasticities are again small, the value being 0.00056 (0.00181) for the open loop (feedback) case.

These results would suggest that there is little deviation from price-taking behavior in either of the output sectors or the input sector, although the estimates do show the market to be slightly less competitive in the case of feedback behavior. The price distortion (Lerner) indices are calculated as the ratio of the sector conjectural elasticities to either supply or demand price elasticities. The results indicate that, for the open loop (feedback) case, relative to what they would have been under perfect competition, potato prices are marked down by 0.086% (0.276%), potato chip prices are marked up by 0.20% (0.72%), and frozen French fries' prices are marked up by 0.34% (1.09%). As noted earlier, these mark downs/mark ups are likely to be biased as they are based on static indices, however as the estimates are already relatively small, they likely represent reasonable approximations of the price distortion indices.

Note that the price distortions in the potato input market are lower than in the output markets for potato chips and frozen French fries. This is due to the fact that the input conjectural elasticity is lower than the output conjectural elasticities due to the smaller market share of a processing firm in the input market for potatoes. The potato-processing industry would appear to be able to extract lower oligopsony rents from potato growers than oligopoly rents from either potato chips or frozen French fries consumers. It is interesting to note that Richards, Patterson, and Acharya (2001) found that potato processors extract oligopsony rents from potato growers in the Pacific Northwest. Our results suggest that these potential rents are lower in the presence of output adjustment costs.

To check for robustness of our results, we estimate the sector price distortion indices under alternative assumptions. If the discount factor $\beta = 0.97$ instead of 0.95, the price distortion indices are slightly lower. Potato prices are marked down by 0.068% (0.253%), potato chip prices are marked up by 0.17% (0.68%) and frozen French fries' prices are marked up by 0.27% (1.00%) under the open loop (feedback) model. The lower discount rate of 3% leads to a smaller impact of processing firms on prices in both the input and output markets.

We also tested the sensitivity of the sector price distortion indices to the price elasticity estimates by taking plus or minus one standard error associated with the coefficients in the potato supply and the potato chips and frozen French fries demand equations. The estimated supply and demand elasticities are quite sensitive to changes in the supply and demand quantity coefficients, resulting in quite a bit of variation in the sector price distortion indices, which increase with more price inelastic supply (demand). However, the estimated price distortions are still low. (The results of this sensitivity analysis are shown in Appendix B.)

5. SUMMARY AND CONCLUSIONS

In this paper, we develop a linear-quadratic dynamic model to estimate oligopoly and oligopsony price distortions in the potato chips and frozen French fries sectors. The empirical model includes specifications for growers' potato supply, market demand for potato chips and frozen French fries, and adjustment equations for the processed quantities. The results indicate that the behavior of potato-processing firms is much closer to price taking than to collusion. Moreover, price distortions due to oligopsony are lower than price distortions due to oligopoly in both the potato chips and frozen French fries sectors.

Finally, the dynamic model considered in this paper addresses the concerns of using either static models or/and modeling only oligopoly or oligopsony. It should be noted, however, that a limitation of the dynamic linear-quadratic model is that it imposes a restrictive functional form for the objective function. Further research may explore a more flexible non-linear problem, where the game can be solved iteratively by linearizing the first order conditions.[21]

APPENDIX A

Solving the Open-Loop Model for *v* and *δ*

We can rewrite equation (7) as follows:

$$(d+\phi-k^2b)\begin{bmatrix}2 & 1\\ 1 & 0\end{bmatrix}\begin{bmatrix}1\\ v\end{bmatrix}=\begin{bmatrix}Z_{11} & Z_{12}\\ Z_{21} & Z_{22}\end{bmatrix}\begin{bmatrix}\delta\\ 0\end{bmatrix}, \tag{A1}$$

where $\mathbf{Z} = [\mathbf{G}^{-1}(\mathbf{I} - \mathbf{G})(\mathbf{I} - \beta\mathbf{G})]'$. Equation (A.1) represents two equations in two unknowns. From the second equation, we can solve for $\delta = (d + \phi - k^2b)/Z_{21}$. Substituting this result in the first equation, we obtain $v = (Z_{11}/Z_{21}) - 2$.

Solving the Feedback Model for *v* and *δ*

Define matrices $\mathbf{A}_i = (\mathbf{K}_i + \beta\mathbf{Y}_i)/(d + \phi - k^2b)$ and $\mathbf{B}_\mathrm{i} = (\mathrm{e_i e_i'} + \beta\mathbf{X}_i)$ and $y_i = \mathbf{G}'^{-1}\mathbf{e}_i$. Then the ith and the kth equation of equation (10) can be re-written as:

$$\left[(d+\phi-k^2b)\mathbf{A}_{ii}+v\sum_{j\neq i}\mathbf{A}_{ij}\right]+\left(\mathbf{B}_{ii}+v\sum_{i\neq j}\mathbf{B}_{ij}\right)\delta=y_{ii}\delta, \tag{A2}$$

and

$$\left[(d+\phi-k^2b)\mathbf{A}_{ki}+v\sum_{j\neq i}\mathbf{A}_{kj}\right]+\left(\mathbf{B}_{ki}+v\sum_{j\neq i}\mathbf{B}_{kj}\right)\delta=y_{ik}\delta. \tag{A3}$$

Equation (A3) can be solved for δ as a linear function of $(d + \phi - k^2b)$ and a non-linear function of v. Substituting δ into equation (A2), gives a quadratic equation in v that is independent of $(d + \phi - k^2b)$. Of the two solutions for the quadratic equation, only one of them falls into the theoretical range.

[21]See Slade (1995) for a discussion of the directions in which modeling of dynamic oligopolistic games might be taken.

APPENDIX B. Sensitivity Analysis for the Elasticities and Price Distortion Indices

Parameters	Potato Sector	Potato Chips Sector	Frozen French Fries Sector
Elasticities			
More Elastic	2.2489	−1.3936	−8.5066
Basic Elasticities	0.6558	−1.0678	−3.3410
Less Elastic	0.3839	−0.8654	−2.0787
Open loop model			
Lower limit	0.00025	0.0015	0.0013
Sector price distortion index (M^o and L^o)	0.00086	0.0020	0.0034
Upper limit	0.00147	0.0025	0.0055
Feedback model			
Lower limit	0.00080	0.0055	0.0043
Sector price distortion index (M^f and L^f)	0.00276	0.0072	0.0109
Upper limit	0.00471	0.0089	0.0175

Note. Based on plus or minus one standard error on the coefficients on quantity in the supply and demand equations.

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