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Alternative Theories and Empirical Approaches to Price Discovery: An Application to Fed Cattle

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Price discovery is a frequent topic of research, but many times is not clearly defined and thus purported to cover a myriad of topics. This article provides two alternative theories as the basis for one line of price discovery research. Empirical models consistent with the two theories are estimated using a common data set. Empirical results differ as expected. This article evidences why the theoretical basis for an empirical model depends on clearly defining the objective(s) of the research.

Key Words: derived demand, fed cattle, partial adjustment model, price discovery

JEL Classifications: Q13, Q11, Q12, C51, C22

Price discovery is a frequently discussed concept by agricultural economists, producers, journalists, and policy makers. But much less frequently is the concept clearly defined. Some definitions of price discovery (e.g., Purcell and Koontz; Tomek and Robinson) tend to follow a 1952 definition by Thomsen and Foote, i.e., the process of buyers and sellers arriving at transaction prices for a given quality and quantity of product at a given time and place. Working later argued that the price formation process involves market participants searching for public and private information to guide them in making decisions that ultimately result in market prices. These definitions focus on the dynamic process of finding transaction prices that collectively clear the market in a given time period.

Numerous expressed price discovery concerns pertain to fed cattle due to rapid consolidation in the meatpacking industry. Therefore, using fed cattle as an example, a distinction is drawn here between price determination and price discovery.

Price determination is commonly defined in microeconomics texts as the interaction of the broad forces of supply and demand that determine the market price level. For fed cattle, supply determinants or factors affecting the quantity of beef produced include input prices (feeder cattle and grain), technology (such as growth promotants), and expected price of outputs produced from those inputs (fed cattle). Broad demand forces or factors affecting the amount of beef consumed include the price of products produced from fed cattle (beef and byproducts), price of competing products (pork and poultry), consumer income, and consumer tastes and preferences.

Following Thomsen and Foote, price discovery is defined here as the process of buyers and sellers arriving at a transaction price for a given quality and quantity of a product at a given time and place. Price discovery involves

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several interrelated concepts, among them market structure (number, size, location, and competitiveness of buyers and sellers); market behavior (buyer procurement and pricing methods); market information and price reporting (amount, timeliness, and reliability of information); and futures markets and risk management alternatives. Price *discovery* begins with the market price *level.* Because buyers and sellers discover prices on the basis of uncertain expectations, transaction prices fluctuate around that market price level. This fluctuation is attributable to the quantity and quality of the commodity brought to market, the time and place of the transaction, amount and type of market information available, and number of potential buyers or active bidders.

One type of price discovery research attempts to determine factors that explain the variation in transaction prices, either within a defined trading period or between trading periods. Models explaining the variability in fed cattle transaction prices (e.g., Ward, Koontz, and Schroeder) often include such variables as (1) boxed beef cutout values; (2) live cattle futures market prices; (3) cattle quality (including sex, weight, quality grade, and yield grade); (4) sale lot size; (5) number of days between purchase and delivery of cattle; (6) individual packing plants or firms; (7) packing plant utilization; (8) day of the week; (9) time of year; and (10) extent and type of captive supplies.

One practical distinction can be made between price determination and price discovery, although not without exceptions. Typically, no single seller (buyer) is large enough to individually influence the broad forces of supply (demand) and thus cannot individually influence the market price level. However, individual firms have the opportunity to influence one or several transaction prices paid or received via the quantity, quality, time, and place of a transaction, type and amount of information used, and the marketing or procurement method (e.g., spot or contract).

Nothing in the literature to our knowledge considers alternative theoretical bases for price discovery and compares empirical results from the alternative theories using a common data set. This article presents two alternative theoretical foundations for price discovery.[1] The first is a derived demand model, which hypothesizes that the transaction price is a function of supply and demand factors as well as attributes of the sale lot of the commodity in question. The second is a partial adjustment or market efficiency model, which asserts that transaction prices are slow to adjust because of rigidities and changes from recent values partly because of new information entering the market. The two theories imply different empirical approaches. Therefore to understand how similar or different the empirical findings are relative to the theory chosen to support the models, a common data set from an experimental fed cattle market is used to estimate the two empirical models. As consolidation has progressed in cattle feeding and meatpacking, access to voluntarily supplied transaction data has declined. The last such data collection effort to estimate models of the type proposed here was in 1990 (Schroeder et al.). Thus this study used experimental market data so as to estimate the two models for data generated under the same market environment.

The next section develops the theoretical foundation for the empirical models. It is followed by a discussion of the experimental market and data used for the analysis. Then the estimation procedure and results are detailed in the subsequent two sections.

Theoretical Models

Final consumers of a good determine the shape and position of the demand function in the retail market. Consumers of beef, for instance, have individual demand schedules for various cuts possessing certain characteristics pertaining to flavor, tenderness, and other attributes. These individual demand schedules are aggregated over consumers to derive a single retail demand function for beef, often called the primary demand for beef.

Derived demand is the demand for inputs used in the production of those goods for

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[1] We do not purport to limit theoretical bases for price discovery to the two presented here.

which primary demand exists. As Tomek and Robinson note, primary and derived demand differ by the amount of marketing and processing charges per unit of product. Numerous derived demand markets for inputs to a consumer good may exist: for instance, there is a derived demand for beef at the wholesale level, in the fed cattle market, and also at the stocker and producer levels. Demand at each of these levels is derived from the primary demand for beef in the retail market.

Ladd and Martin further refine the concept of derived demand by showing how the price of an input is the sum of the values of that input's characteristics to the purchaser. Suppose the production function for boxed beef is written

$$(1)\qquad Q_B = F_B(\varphi_{1B}, \varphi_{2B}, \ldots, \varphi_{mB}),$$

where Q_B is the quantity of boxed beef produced by a beef packer, and the φ_{jB} are the $j = 1, 2, \ldots, m$ input characteristics used in producing Q_B. The equation then states that the quantity of boxed beef produced depends upon the amounts of various input characteristics used to produce it. If $x_{1B}, x_{2B}, \ldots, x_{nB}$ are the quantities of inputs, including fed cattle, used to produce Q_B, then the total amount of the *j*th input characteristic used in production can be written

$$(2)\qquad \varphi_{jB} = \Omega_{jB}(x_{1B}, x_{2B}, \ldots, x_{mB}, \varphi_{j1B}, \varphi_{j2B}, \ldots, \varphi_{jnB}),$$

where φ_{jiB} is the quantity of characteristic j that enters into the production of boxed beef through the use of one unit of input i. The production function Equation (1) can then be rewritten

$$(3)\qquad Q_B = G_B(x_{1B}, x_{2B}, \ldots, x_{mB}, \varphi_{11B}, \varphi_{12B}, \ldots, \varphi_{mnB}).$$

Assume for simplicity that the beef packing firm is a single output firm. Then its profit function is

$$(4)\qquad \Pi = P_B F_B(\varphi_{1B}, \varphi_{2B}, \ldots, \varphi_{mB}) - \sum_{i=1}^{n} w_i x_{iB},$$

where P_B is the price of boxed beef and w_i is the price of input *i*.

The profit maximizing use of input *i* is then given by the first-order condition

$$(5)\qquad \frac{\partial \pi}{\partial x_{iB}} = P_B \sum_{j=1}^{m} \left(\frac{\partial F_B}{\partial \varphi_{jB}}\right)\left(\frac{\partial \varphi_{jB}}{\partial x_{iB}}\right) - w_i = 0$$

and the price of input *i* is

$$(6)\qquad w_i = P_B \sum_{j=1}^{m} \left(\frac{\partial F_B}{\partial \varphi_{jB}}\right)\left(\frac{\partial \varphi_{jB}}{\partial x_{iB}}\right).$$

In this formulation, $(\partial \varphi_{jB}/\partial x_{iB})$ is the marginal yield of *j* in the production of boxed beef from the *i*th input, and $(\partial F_B/\partial \varphi_{jB})$ is the marginal product of one unit of *j* used in producing boxed beef. Accordingly, $P_B \times (\partial F_B/\partial \varphi_{jB})$ is the value of marginal product for *j* used in boxed beef production and can be interpreted as an imputed price paid for that characteristic. If the imputed price is designated as T_{jB}, Equation (6) can be rewritten as

$$(7)\qquad w_i = \sum_{j=1}^{m} T_{jB}\left(\frac{\partial \varphi_{jB}}{\partial x_{iB}}\right),$$

which says the price paid for each input to boxed beef production (including fed cattle) is the sum of the marginal yield values for that input's useful characteristics to boxed beef.

In the fed cattle market, heterogeneous lots of cattle consist of different amounts of desirable characteristics. For example, cattle of two different USDA quality grades, e.g., Prime and Select, might be processed into different boxed beef products for different customers, e.g., tablecloth restaurants or retail supermarkets. Since saleable boxed beef is produced by using the useful characteristics contained in fed cattle, cattle of different qualities are worth different amounts of money per live hundredweight. Ladd and Martin summarize the product characteristics approach to derived demand for inputs in two themes: (1) the price of an input equals the sum of the values of the characteristics of that input to the purchaser, and (2) input demand is affected by that input's characteristics. If these themes hold, the characteristics of the input in question, for example here for fed cattle, determine its value in the product (retail) market. Accordingly, the same characteristics determine its value in the fed cattle market. The derived demand model for fed cattle should thus include variables that capture the overall industry demand for fed cattle, as well as variables that relate specifically to the characteristics of particular lots of animals. Of course, other factors, particularly those relating to current and expected supply conditions, must be included to ensure the derived demand model is fully specified.

A second distinct theoretical framework for livestock price discovery stems from the partial adjustment model and has been used extensively for empirical estimation. The partial adjustment model was developed into its modern form by Nerlove. He attempted to derive accurate estimates of supply and demand elasticities for agricultural products. He argued that short-run elasticities cannot be accurately measured because they correspond to a single point in time and that estimation of long-run elasticities is difficult because of constantly changing prices and adjustment paths. As a result, he advocated a dynamic model over a static one and argued that dynamic models are better at explaining data, produce coefficients that are more reasonable in sign and magnitude, and generate residuals that exhibit less serial correlation.

To capture the dynamic aspects of agricultural supply and demand, Nerlove employed a distributed lag model. He assumed a behavioral model that implied a single period distributed lag only, rather than testing for significance at varying lag lengths. Assuming static expectations, Nerlove and Addison postulated that the quantity of a commodity demanded changes only in proportion to the difference between the long-run equilibrium quantity desired and the current quantity demanded. To derive this result, Nerlove began with a long-run demand function

$$q_t^* = a + bp_t + cy_t, \tag{8}$$

where q_t^* is the long-run equilibrium quantity demanded, p_t is the current price, and y_t is current income. This equation cannot be estimated directly since q_t^* is not observable. But if the relation between the current quantity q_t and the long-run equilibrium quantity is given by the difference equation

$$q_t - q_{t-1} = \gamma(q_t^* - q_{t-1}), \tag{9}$$

where γ is the coefficient of adjustment, then the first expression can be substituted into the second to obtain

$$q_t = a\gamma + b\gamma p_t + c\gamma y_t + (1 - \gamma)q_{t-1} + u_t, \tag{10}$$

which is an equation in autoregressive form and is therefore estimable.

Partial adjustment models are widely used because of the intuitive appeal of the notion that quantities and prices adjust to new conditions slowly over time. Use of such models is common in agricultural supply analysis. Askari and Cummings surveyed over 600 studies that employed the Nerlove formulation for various agricultural commodities, including beef. For the fed cattle market, it seems intuitive that adjustment of quantities produced in response to recent prices cannot be instantaneous. The biological production lag for cattle, technological rigidities, habit inertia, asset fixity, resource control, and institutional constraints all contribute to a gradual adjustment process. This gradual adjustment process is often cited as justification for inclusion of a lagged dependent variable in regression models.

Inclusion of a lagged dependent variable in partial adjustment models has been the subject of much discussion. Waud asserts that the appropriate specification of Nerlove's model is

$$\begin{aligned} q_t = {} & a\gamma\delta + b\gamma\delta p_t + c\gamma\delta y_t \\ & + [(1 - \delta) + (1 - \gamma)]q_{t-1} \\ & - (1 - \delta)(1 - \gamma)q_{t-2} + u_t \end{aligned} \tag{11}$$

and that Equation (10) is simply a special case of this expression where $\delta = 1$, representing the case where expectations are static in the adaptive sense.[2] Waud notes that the users of the partial adjustment model implicitly assume expectations are formed thusly, since they are not specified explicitly as being formed in any other way. If the value of either δ or γ is 1, then the coefficient on q_{t-2} will not be significant, and the partial adjustment model is the appropriate specification. As will be discussed here, it is appropriate for the purposes of this article to impose a value of 1 for δ; thus the partial adjustment model will be proper for estimation.

Fama is widely credited with relating the level of efficiency in a market to the ways in which prices of assets in that market reflect different types of information. An efficient market, he explained, is one that fully reflects all available information.[3] He developed weak form, semistrong form, and strong form tests of efficiency for markets where prices reflect historical, current public, and all relevant (including nonpublic or insider) information, respectively. Sufficient (but not necessary) conditions for market efficiency are (1) no transaction costs in trading; (2) complete, costless information is available to all participants; and (3) implications of current information for current and future prices is agreed upon by all participants.

The relevance of the market efficiency model to the fed cattle market can be seen by outlining the relationship between information and prices in Fama's work. Consider the relationship

$$(12)\quad E(p_{j,t+1}|\Phi_t) = [1 + E(r_{j,t+1}|\Phi_t)]p_{j,t},$$

where E is the expectations operator, $p_{j,t}$ is the price of the asset at time t, $p_{j,t+1}$ is the analogous price at time $(t + 1)$, $r_{j,t+1}$ is the single-period percentage return on the asset, and Φ_t is the available information set in time period t. The expression states that the expected price of the asset in the next period depends only on the expected return to the asset, given a specific information set. If the expected return to the asset is realized, then, the expected price of the asset in period $(t + 1)$ will be realized unless the information set changes. It must then be the case that changes in information are responsible, in part, for changes in the price of an asset between periods.

Garbade, Pomrenze, and Silber found that observed prices contain considerable information and that market participants are alert to the quality of the information contained in those prices. In the context of Fama's market efficiency hypothesis, then, observed prices form part of the information set Φ_t upon which future prices are conditioned. Analogously, the previous period's observed prices have an effect on the current period's prices insofar as they are part of the relevant information set. Market participants derive important information about current expected prices from lagged prices, and lagged prices are therefore appropriate to include in the price discovery model. When Fama's market efficiency concept is applied to livestock price discovery, then, it can be seen that the partial adjustment model is appropriate, given the important role played by the information contained in the lagged price.

Experimental Market and Data

The Fed Cattle Market Simulator (FCMS), an experimental market for fed cattle, was developed at Oklahoma State University to mitigate the problem of collecting voluntary transaction-level data between beefpackers and cattle feeders. Research with data from the market simulator has been compared with similar, previous research using industry data (Ward et al. 1996). There also can be found a more detailed description of the FCMS than is presented here.

The FCMS consists of 12 teams of two to four people. Four teams assume the role of beefpacking procurement managers, and eight teams assume the role of cattle feedlot marketing managers. Each of the 12 teams at-

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[2] Delta is the coefficient of expectations, the proportion of expectational error to be taken as permanent rather than transitory. See Waud (pp. 204–06) for a complete derivation of Equation (11).

[3] Fama's theory and research involved capital market goods (i.e., stock market securities), but the analysis can be generalized to any asset of value, including an input to a production process such as fed cattle.

tempts to earn a profit buying or selling paper pens of fed cattle. The packer and feeder teams trade paper lots of 100 head of fed cattle in 7-minute open-negotiation trading sessions. Packer players walk around the trading room to visit various feedlot teams in order to procure the cattle needed to ensure their plants run at or near the minimum-cost slaughter volume. Each trading session represents 1 week in the real fed cattle market. Firms may trade fed cattle on a cash or forward delivery basis and may also participate in futures market hedging and/or speculating. During and at the end of each trading session, cash and futures market information is provided to the entire group of participants on electronic displays and chalk board, much like what is provided by the U.S. Department of Agriculture's (USDA's) Agricultural Marketing Service and Chicago Mercantile Exchange. In addition, each team receives an income statement detailing their performance that week.

A cyclical cattle supply, intended to resemble the real beef industry, is part of the structure of the FCMS. Feeder cattle are placed on feed at 700 lbs., gain 25 lbs. per week, and appear on the fed cattle market show list at 1,100 lbs. Cattle remain on the show list until they are sold or reach a weight of 1,200 lbs. If cattle are not sold by the end of the trading session in which they have attained 1,200 lbs., the FCMS automatically sells them to a hypothetical fifth packer at a heavily discounted price. Packers prefer to purchase heavier cattle because of cost and processing economies associated therewith. Feeders, conversely, aim to sell fed cattle at 1,150 lbs., which minimizes their break-even cost. FCMS cattle on feed reports, issued every 4 weeks, were designed to be similar to USDA *Cattle on Feed* reports by the National Agricultural Statistics Service.

Packers in the FCMS purchase fed cattle as inputs and produce boxed beef and byproducts as their outputs. The boxed beef price is based on a real market demand function and varies inversely with the number of lots and the weight of cattle traded. It relates the supply of fed cattle and their weight to the demand for beef from the wholesale market and thus is an important component of the derived demand price signal received by packers and feeders. Feeders' inputs consist of the feed required for their cattle to gain the requisite 25 lbs. per week and the cost of feeder cattle, which varies inversely with supply. Output from the feedlots is fed cattle sold to packers. Feeders calculate and monitor the break-even price for their cattle in an effort to earn a profit. Total profit available to the industry varies as the supply of feeder cattle varies and as the boxed beef price varies.

Cattle feeding firms are homogeneous in structure, but the four packers are not; each packer has a unique minimum-cost slaughter volume, ranging from eight to 12 lots per week. The most successful packers tend to procure close to their minimum-cost slaughter volume on a period-to-period basis. Economic behavior on the part of participants is encouraged through periodic updates on the best and worst performing packer and feeder teams, respectively, as well as through the awarding of traveling trophies at regular intervals.

The FCMS generates data that occur in cross-sectional time series. Data are recorded for each completed transaction, but data are not available on individual bids and offers. Observed trading by participants indicates a variety of situations occur in any given trading week. Transactions may result from single bid and acceptance negotiations, or single offer and acceptance, to multiple bids and offers with multiple counterbids and counteroffers. Data for this study were taken from three semester-long market simulator classes during 1994, 1995, and 1996. Agricultural economics, animal science, and agricultural education students enrolled in each class. Total trading weeks varied slightly over the 3 years; thus only the common transaction periods are included here, allowing for direct comparison of the estimated coefficients. During the 60 common transaction periods, 2,198 transactions took place during 1994; 2,210 during 1995; and 2,197 during 1996. Transactions in any given trading week ranged from 20 to 50 and averaged 33.6–33.8 transactions per trading period over the three semesters. Summary statistics for the 3 years' data are shown in Table 1. Price and quantity data were tested for con-

Table 1. Summary Statistics, Fed Cattle Market Simulator (FCMS) Data, 1994–1996

	1994	1995	1996
Trading periods	60	60	60
Transactions	2,198	2,210	2,197
Average price (\$/cwt)	78.59	78.53	78.31
SD	3.46	3.65	3.62
Average quantity (pens)	36.60	36.80	36.67
SD	6.27	6.12	7.61

Table 2. Variable Descriptions for Derived Demand and Partial Adjustment Models

Variable	Description
PR_{it}	Fed cattle transaction price *i* in period *t* (\$/cwt)
PR_{t-1}	Lagged average transaction price (\$/cwt)
BBP_{t-1}	Boxed beef price, lagged one period, for Choice YG1-3, 550–700 lb. carcasses (\$/cwt)
FUT_{t-1}	Live cattle futures closing price, lagged one period, for the nearby closing month (\$/cwt)
MKT_{t-1}	Total pens of cattle marketed/purchased, lagged one period
TSL_t	Total pens of cattle on the show list the beginning of the period
WT_{it}	Weight of the lot of animals traded in transaction *i* during time period *t* (i.e., 1,100 lbs., 1,125 lbs., etc.)
$DTYPE_{ikt}$	Zero–one dummy variable for transaction type; $k = 1–2$, 1 = cash, 2 = forward contract, Base = forward contract
$DPCKR_{ilt}$	Zero–one dummy variable for individual packers; $l = 1–4$, 1 = PCKR1, 2 = PCKR2, 3 = PCKR3, 4 = PCKR4, Base = PCKR1
$DFDR_{imt}$	Zero–one dummy variable for individual feedlots; $m = 1–8$, 1 = FDR1, 2 = FDR2, 3 = FDR3, 4 = FDR4, 5 = FDR5, 6 = FRD6, 7 = FDR7, 8 = FDR8, Base = FDR1

sistency using analysis of variance (ANOVA) and found not to be significantly different over the 3 years (Carlberg and Ward). This consistency occurred even with imposing specific experimental designs on the classes in 1995 (Anderson et al.) and 1996 (Ward et al., 1999).

Estimated Models

Jones et al. assert that since the short-run supply of cattle is inelastic, the derived demand model for cattle can be expressed in price-dependent form. The model must include those variables that capture the input demand characteristics of fed cattle, as well as other variables theoretically justified by their effects on transaction prices in the experiment. Accordingly, the derived demand model is specified as

$$
\begin{aligned}
(13)\quad PR_{it} = {} & \beta_0 + \beta_1 BBP_{t-1} + \beta_2 FUT_{t-1} \\
& + \beta_3 MKT_{t-1} + \beta_4 TSL_t + \beta_5 WT_{it} \\
& + \sum_{k=1}^{2} \beta_{6k} DTYPE_{ikt} + \sum_{l=1}^{4} \beta_{7l} DPCKR_{ilt} \\
& + \sum_{m=1}^{8} \beta_{8m} DFDR_{imt} + e_{it},
\end{aligned}
$$

where the variables are as defined in Table 2. Lagged boxed beef price is included because it is the mechanism through which demand conditions at the wholesale (and hence retail) markets are coordinated with supply conditions in the fed cattle market. This variable should have a positive coefficient; as the boxed beef price increases, packers are able to pay more for fed cattle. The boxed beef price is lagged in the model because the most recent period's price is the information most useful to participants for price discovery. The lagged futures market price is also included; it provides an indication of expected market conditions and forms part of the information set used to calculate expected prices. The lagged futures price coefficient is also expected to be positive.

Two variables that capture the supply conditions in the experimental market are included in the derived demand model. The total show list variable gives the total number of lots of cattle available for sale by cattle feedlots at the beginning of the market period. The greater the number of cattle on the show list, the lower should be the transaction price. Lagged marketings are also included as an indication of the previous period's trading volume. It is expected that a greater volume of sales in the previous period will have caused prices to decline in that period, and that the pattern of lower prices should prevail in the current period.

As noted above, the weight of the lot of cattle traded is important to both packers and feeders. Animal weight is important according to the product characteristics model and is expected to significantly affect transaction prices. The expected sign of the coefficient is ambiguous; cattle feeders do not like to keep heavier cattle on the show list, but packers prefer to slaughter them. The sign of the parameter estimate will therefore depend on the negotiating skill and strength of the packer and feeder teams.

Three classes of indicator variables are included in the model: transaction type, packer-buyer, and feedlot-seller. The transaction type variable specifies cash or forward contract transaction. Carlton shows that uncertainty and transaction costs create incentives for firms to use contracts. If these incentives are strong enough, contract prices will exceed cash prices. However, empirical work with data from the real-world fed cattle market generally indicates that contract prices are lower than cash prices (Eilrich et al.; Schroeder et al.; Ward, Koontz, and Schroeder). As such, there is no clear expected sign for the variable. The variables for packers and feeders are included to capture the effects of individual negotiating and reputation effects of the teams. No *a priori* expectations for parameter sign are attached to any particular packing or feeding firm.

The partial adjustment model includes all of the same variables as the derived demand model, but also contains lagged average price to capture rigidities and inertia in the beef supply chain and the informational content of past prices. A lag length of one on the price time series is assumed because it captures the essence of the partial adjustment model advocated by Nerlove and the market efficiency model of Fama. The partial adjustment model is then

$$\begin{aligned}(14)\quad \mathrm{PR}_{it} = {} & \gamma\beta_0 + (1-\gamma)\beta_1\mathrm{PR}_{t-1} + \gamma\beta_2\mathrm{BBP}_{t-1} \\ & + \gamma\beta_3\mathrm{FUT}_{t-1} + \gamma\beta_4\mathrm{MKT}_{t-1} \\ & + \gamma\beta_5\mathrm{TSL}_t + \gamma\beta_6\mathrm{WT}_{it} \\ & + \sum_{k=1}^{2}\beta_{7k}\mathrm{DTYPE}_{ikt} + \sum_{l=1}^{4}\beta_{8l}\mathrm{DPCKR}_{ilt} \\ & + \sum_{m=1}^{8}\beta_{9m}\mathrm{DFDR}_{imt} + e_{it}.\end{aligned}$$

A mixed model is used to estimate Equations (13) and (14) for each of the 3 years' data. The mixed model is a generalization of the standard linear formulation, but it allows both the means and the variances of data to be modeled. The parameters of the mean model are the fixed effects parameters and are associated with known regressors, as in usual estimation procedures. The parameters of the variance-covariance model can be specified in the mixed model as following a number of alternative covariance structures. This allows a more flexible specification of the covariance of the error term than does the standard linear model. A random effects specification is chosen for the experimental market data. In the random effects specification, a dual-component error term is assumed:

$$(15)\quad e_{it} = u_t + v_{it},$$

where u_t is an effect that is unique to a specific cross-section (panel) of data and v_{it} is the portion of the error term associated with the overall model. In the experimental market, u_t is specified as being unique to each trading session. The random-effects specification is tested with a likelihood ratio (LR) test as the unrestricted variance-covariance structure versus the restricted case of the general linear model. The test statistic is

$$(16)\quad -2(\ln L_R - \ln L_U) \sim \chi^2(J),$$

where J is the degrees of freedom equal to the difference in the number of parameters in the restricted versus unrestricted specification of the covariance structure. In this case, $J = 1$. The mixed linear model can be written as

$$(17) \quad \mathrm{PR}_{it} = \mathbf{X}\beta + \mathbf{Z}\eta + \mathbf{e}_t,$$

where **X** is the matrix of observations on the known regressors in Equations (13) and (14), β is the vector of fixed-effects parameters, $\boldsymbol{\eta}$ is the vector of random-effects parameters, **Z** is the known design matrix of $\boldsymbol{\eta}$, and $\mathbf{e}_t$ is the vector of error terms. The elements of $\mathbf{e}_t$ are no longer required to be independent and homogeneous (SAS Institute, Inc.). The MIXED procedure in SAS is used to estimate Equation (13), and the NLMIXED procedure is used to estimate Equation (14), employing restricted maximum likelihood (REML) as the estimation method.[4]

Dickey-Fuller tests for stationarity of the price time series were carried out. If the series was not stationary, estimation results could be spurious (Kennedy). The VARMAX procedure in SAS (SAS Institute, Inc.) was used to carry out the test for each of the three data sets, and none was found to be nonstationary.

The focus of this article is on alternative theoretical bases and empirical models for price discovery, rather than model selection *per se*. Thus it is argued here that research objective and economic theory should take precedence over specification tests of an empirical model in model selection. However, that does not diminish the importance of specification testing.[5]

Results

Results of the REML estimation of the mixed model as shown in Equations (13) and (14) are presented in Table 3. It is clear that the derived demand and partial adjustment models produce substantially different estimates for some of the coefficients. The coefficients on lagged marketings are lower for the partial adjustment model than for the derived demand model in each of the 3 years. For the other supply variable (total show list), the coefficients are higher for the partial adjustment model in 2 of the 3 years. Overall, the expected signs are obtained on the supply variables in all but one case.

In 2 of the 3 years, coefficients are higher for lagged boxed beef prices in the partial adjustment model than in the derived demand model. Similarly, estimates for lagged futures market prices are higher in the partial adjustment model for 2 of 3 years. Conversely, coefficients on the weight variable are lower for 2 of the years and higher for the third. Estimates of the effect of cash versus forward contract transaction are similar in magnitude for both models for each of the 3 years as they are for the other indicator variables.

The expected signs are obtained for nearly all variables under either specification. The adjustment coefficient (γ) is positive in each of the three partial adjustment models and of similar magnitude for 2 out of the 3 years. The coefficients for the 1994 and 1996 data indicate that from the perspective of the partial adjustment model, adjustment is rather slow (recall that the coefficient is 1 minus the partial adjustment factor) at approximately 25% per trading period. The much quicker adjustment speed in the 1995 semester could be the result of less reliance on the previous period's price as a source of information. It could also be the result of some behavioral traits peculiar to the group of participants that year.

The coefficient on lagged boxed beef is significant and of the expected sign for five of the six models estimated, providing support for its hypothesized effect on fed cattle transaction prices. The derived demand relationship therefore appears to hold in the experimental

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[4] Because of the presence of the partial adjustment coefficient γ in Equation (14), NLMIXED rather than MIXED must be used. The procedures work in otherwise identical ways.

[5] McGuirk, Driscoll, and Alwang discuss the importance of a battery of misspecification tests to minimize erroneous conclusions. Other, standard tests can also be used for model selection, i.e., R^2, Akaike's Information Criterion (AIC), and the Schwartz's Bayesian Criterion (SBC). Since REML is used, R^2 cannot be calculated, and a likelihood-based criterion must be employed instead. The AIC increases as R^2 increases, but degrades as model size increases (Greene). Schwartz's Bayesian criterion is calculated in a similar manner, but has a greater penalty for added regressors. Both the AIC and SBC were calculated for each of the 3 years' data for both models estimated here.

Table 3. Mixed Model Estimates for Derived Demand and Partial Adjustment Models, 1994–1996

	1994		1995		1996	
Variable	Derived Demand	Market Efficiency	Derived Demand	Market Efficiency	Derived Demand	Market Efficiency
Intercept	15.601**	15.411	22.883**	14.652	30.819**	92.488**
	(7.437)	(14.052)	(7.390)	(10.325)	(9.775)	(43.955)
Gamma	—	0.265**	—	0.575**	—	0.233**
		(0.057)		(0.073)		(0.097)
BBP_{t-1}	0.339**	0.522**	0.346**	0.407**	0.183**	−0.139
	(0.043)	(0.096)	(0.029)	(0.042)	(0.053)	(0.232)
FUT_{t-1}	0.372**	0.189	0.353**	0.376**	0.501**	0.645**
	(0.084)	(0.162)	(0.067)	(0.089)	(0.082)	(0.247)
MKT_{t-1}	−0.096**	−0.235**	−0.051**	−0.056*	0.022	−0.196
	(0.029)	(0.067)	(0.024)	(0.032)	(0.034)	(0.153)
TSL_t	−0.024**	−0.015	−0.061**	−0.044**	−0.067**	−0.091**
	(0.012)	(0.022)	(0.013)	(0.017)	(0.011)	(0.034)
WT_{it}	−0.001	−0.003	−0.006**	−0.008**	−0.0057**	−0.0024*
	(0.001)	(0.004)	(0.002)	(0.003)	(0.002)	(0.001)
Cash sale	−0.312**	−0.307**	0.328**	0.342**	−0.804**	−0.799**
	(0.076)	(0.076)	(0.102)	(0.101)	(0.100)	(0.099)
Packer 2	−0.490**	−0.490**	−0.362**	−0.357**	−0.089	−0.095
	(0.058)	(0.058)	(0.076)	(0.076)	(0.085)	(0.085)
Packer 3	−0.267**	−0.268**	−0.287**	−0.288**	−0.125*	−0.125*
	(0.056)	(0.056)	(0.076)	(0.074)	(0.074)	(0.074)
Packer 4	−0.155**	−0.155**	−0.153**	−0.148**	0.329**	0.329**
	(0.054)	(0.054)	(0.074)	(0.073)	(0.076)	(0.076)
Feedlot 2	0.059	0.056	0.156**	0.155	0.646**	0.647**
	(0.074)	(0.075)	(0.099)	(0.099)	(0.100)	(0.100)
Feedlot 3	−1.113	−0.112	0.842**	0.830**	0.849**	0.848**
	(0.077)	(0.077)	(0.103)	(0.103)	(0.111)	(0.111)
Feedlot 4	−0.012	−0.011	0.478**	0.477**	1.173**	1.172**
	(0.075)	(0.075)	(0.100)	(0.100)	(0.110)	(0.110)
Feedlot 5	−0.375**	−0.372**	0.605**	0.611**	0.792**	0.079**
	(0.075)	(0.075)	(0.100)	(0.100)	(0.113)	(0.112)
Feedlot 6	0.057	0.055	0.442**	0.441**	0.752**	0.762**
	(0.072)	(0.072)	(0.097)	(0.097)	(0.112)	(0.112)
Feedlot 7	−0.170**	−0.177**	0.417**	0.414**	0.678**	0.682**
	(0.074)	(0.074)	(0.099)	(0.099)	(0.109)	(0.109)
Feedlot 8	−0.066	−0.069	0.270**	0.272**	0.748**	0.743**
	(0.077)	(0.077)	(0.099)	(0.099)	(0.114)	(0.114)

Note: Double and single asterisks denote significance at the 5% and 10% levels, respectively.

market. Similarly, the futures price variable has the expected sign for each of the models and is significant for five of six models estimated. Thus participants take the futures market into account when negotiating bid/ask prices.

The two supply variables behave as anticipated in the estimated models. Lagged marketings have a negative and significant (at least at the 0.10 level) effect on prices in four of six models. Similarly, the total show list variable has the expected negative sign in all models and is significant in all but one. The theoretical result that prices will decline as supply increases is clearly borne out in the experimental market.

The weight variable has a negative effect on price in each model and is significant in four out of six models. This means that packers were able to procure heavier cattle at a discount, although such animals are more valuable to them. Feeders are adversely affected by keeping cattle on the show list too long. They become costly to feed as the minimum break-even price of 1,150 lbs. is passed, less money is received from packers for heavier cattle as negotiating strength shifts to packers (Lyford et al.), and heavier cattle put downward pressure on the boxed beef market.

The cash sale variable is significant in each of the six models and has a negative effect on transaction prices for 1994 and 1996, but not 1995. This may indicate that the reduced transactions cost and uncertainty associated with contracting are sufficient to increase forward contract prices. In 1995, a marketing agreement was imposed between the largest packer and two feedlots. This may have reduced the potential gains to additional contracting that year, explaining the positive sign on the cash transaction estimate. It is also possible that the effects of cash sales on transactions prices are sensitive to specific participants in the experimental market. Simply put, some participants may be better able to take advantage of different pricing methods than others.

Use of available information is an important component of price discovery. Computing standardized betas (not shown in Table 3 but available upon request) provide some insight into the price discovery process (Pindyck and Rubinfeld). Three variables were among the four most important variables in five of the six models estimated. They were the lagged boxed beef price, lagged futures market price, and current show list. Results were more consistent for 1994 and 1995 than for 1996. Only minor differences were found between the derived demand models and partial adjustment models. Importantly, these were the demand and supply variables in the model that combine to determine the overall price level. Apart from these four variables, there was little difference in the standardized betas for other model variables, both across model specifications and data periods.

Table 4. Likelihood Ratio Tests of Random Effects Model, 1994–1996

Test Statistic	1994	1995	1996
Likelihood ratio $\chi^2(1) = 6.63$	1,668	2,152	1,475

Note: The size of the likelihood ratio test is 0.025.

Results of LR tests for the appropriateness of the random-effects specification of the variance-covariance model are shown in Table 4. The unrestricted model, which contains a random effect specific to the transaction week, is found to be the correct specification. The calculated test statistic exceeds the critical χ^2 value with 1 df of 6.63 for each of the 3 years. This supports the hypothesis that intraweek variability is an important component of the mixed model applied to data from the experimental market. Were this variability not accounted for, estimated coefficients would be less efficient than they are under the correct specification.

Based on the AIC and SBC selection criteria, the partial adjustment model provides a better fit than the derived demand model for each of the 3 years' data. This may be further justification for inclusion of a lagged dependent variable in empirical livestock price discovery work. Informational content of past prices appears to contribute considerable information to current period price discovery. However, there may be reason to prefer the derived demand empirical specification depending on the purpose for estimating the model. If emphasis is more on the effects of transaction-specific variables, the derived demand model may be preferred. If emphasis is on the dynamic elements of the market, the partial adjustment model may be preferred. Thus research objectives and theoretical bases combine to determine the empirical specification chosen for price discovery modeling.

Summary and Conclusions

The objective of the research reported in this paper was to present and compare alternative theories and empirical models of price discovery, with a focus on the fed cattle markets. Understanding the price discovery process in livestock markets is important for industry stakeholders so that they can interpret price signals accurately and make appropriate judgments regarding price discovery issues. This paper used data from an experimental market for fed cattle in order to illustrate differences between two plausible theoretical models.

Derived demand and partial adjustment models for transaction prices in the experimental market were specified and estimated for semester-long data periods in 1994, 1995, and 1996 using a mixed linear model. Nearly 2,200 observations were included in each of the three data sets. A random-effects covariance structure was selected to allow intraweek variability of transactions prices to be explicitly considered in estimation. Likelihood ratio tests were carried out to assess the validity of the random-effects versus the restricted covariance structure, and it was found that the random-effects specification is appropriate. The regressors in each of the models were specified as fixed effects parameters. Finally, model selection criteria were outlined. Research objective and theoretical approach are primary criteria for empirical model selection, but other criteria are important when choosing a model.

Most variables included in the models had the expected sign and were significant at the 5% level for each data set. Inclusion of the lagged dependent variable in the partial adjustment model changed the magnitudes of estimates of other regressors relative to the derived demand model, but in general did not affect their significance. Parameter estimates for each of the 3 years' data were similar with a few exceptions.

The choice of theoretical model in conjunction with research objective is of key importance to any applied research. Often, the researcher will have alternative theoretical models from which to choose, leading to more than one appropriate empirical model specification for the problem at hand. Thus choice of model should be based in part on research objectives in addition to econometric criteria.

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References

Anderson, J.D., C.E. Ward, S.R. Koontz, D.S. Peel, and J.N. Trapp. "Experimental Simulation of Public Information Impacts on Price Discovery and Marketing Efficiency in the Fed Cattle Market." *Journal of Agricultural and Resource Economics* 23(1998):262–78.

Askari, H., and J.T. Cummings. "Estimating Agricultural Supply Response with the Nerlove Model: A Survey." *International Economic Review* 18(1977):257–92.

Carlberg, J.G., and C.E. Ward. "Intertemporal Consistency of Transaction Price Determinants in an Experimental Market for Fed Cattle." Selected paper, 2001 Southern Agricultural Economics Association annual meetings, Fort Worth, Texas, January 2001.

Carlton, D.W. "Contracts, Price Rigidity, and Market Equilibrium." *Journal of Political Economy* 87(1979):1034–62.

Eilrich, F., C.E. Ward, W.D. Purcell, and D.S. Peel. *Forward Contracting vs. Hedging Fed Cattle: Comparisons and Lender Attitudes.* Blacksburg, VA: Research Institute on Livestock Pricing, research bulletin, December 1987.

Fama, E.F. "Efficient Capital Markets: A Review of Theory and Empirical Work." *Journal of Finance* 25(1970):383–417.

Garbade, K.D., J.L. Pomrenze, and W.L. Silber. "On the Information Content of Prices." *American Economic Review* 69(1979):50–59.

Greene, W.H. *Econometric Analysis,* 4th ed. Upper Saddle River, NJ: Prentice Hall, 2000.

Jones, R., T. Schroeder, J. Mintert, and F. Brazle. "The Impacts of Quality on Cash Fed Cattle Prices." *Southern Journal of Agricultural Economics* 24(1992):149–62.

Kennedy, P. *A Guide to Econometrics,* 4th ed. Cambridge, MA: MIT Press, 1998.

Ladd, G.W., and M.B. Martin. "Prices and Demands for Input Characteristics." *American Journal of Agricultural Economics* 58(1976): 21–30.

Lyford, C.P., R.T. Hicks, J.N. Trapp, C.E. Ward, and D.S. Peel. "Negotiating Strength in an Experimental Market for Fed Cattle." Oklahoma State University, Department of Agricultural Economics, Departmental paper, 2001.

McGuirk, A.M., P. Driscoll, and J. Alwang. "Misspecification Testing: A Comprehensive Approach." *American Journal of Agricultural Economics* 75(1993):1044–55.

Nerlove, M. "Distributed Lags and Estimation of Long-Run Supply and Demand Elasticities:

Theoretical Considerations." *Journal of Farm Economics* 40(1958):301–11.

Nerlove, M., and W. Addison. "Statistical Estimation of Long-Run Elasticities of Supply and Demand." *Journal of Farm Economics* 40(1958): 861–80.

Pindyck, R.S., and D.L. Rubinfeld. *Econometric Models and Economic Forecasts,* 4th ed. Boston: McGraw-Hill, 1998.

Purcell, W.D., and S.R. Koontz. *Agricultural Futures and Options: Principles and Strategies,* 2nd ed. Upper Saddle River, NJ: Prentice Hall.

SAS Institute, Inc. *SAS/ETS User's Guide, Version 8.* Cary, NC: SAS Institute, 1999.

Schroeder, T.C., R. Jones, J. Mintert, and A.P. Barkley. "The Impact of Forward Contracting on Fed Cattle Transaction Prices." *Review of Agricultural Economics* 15(1993):325–37.

Thomsen, F.L., and R.J. Foote. *Agricultural Prices,* 2nd ed. New York: McGraw-Hill, 1952.

Tomek, W.G., and K.L. Robinson. *Agricultural Product Prices,* 3rd ed. Ithaca, NY: Cornell University Press, 1990.

Ward, C.E., S.R. Koontz, and T.C. Schroeder. "Impacts from Captive Supplies on Fed Cattle Transaction Prices." *Journal of Agricultural and Resource Economics* 23(1998):494–514.

Ward, C.E., S.R. Koontz, T.L. Dowty, J.N. Trapp, and D.S. Peel. "Marketing Agreement Impacts in an Experimental Market for Fed Cattle." *American Journal of Agricultural Economics* 81(1999):347–58.

Ward, C.E., S.R. Koontz, D.S. Peel, and J.N. Trapp. "Price Discovery in an Experimental Market for Fed Cattle." *Review of Agricultural Economics* 18(1996):449–66.

Waud, R.N. "Misspecification in the 'Partial Adjustment' and 'Adaptive Expectations' Models." *International Economic Review* 9(1968): 204–17.

Working, H. "A Theory of Anticipatory Prices." *American Economic Review* 39(1959):188–99.