Approximation for Convenience Yield in Commodity Futures Pricing

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The pricing of commodity futures contracts is important both for professionals and academics. It is often argued that futures prices include a convenience yield, and this article uses a simple trading strategy to approximate the impact of convenience yields. The approximation requires only three variables—underlying asset price volatility, futures contract price volatility, and the futures contract time to maturity. The approximation is tested using spot and futures prices from the London Metals Exchange contracts for copper, lead, and zinc with quarterly observations drawn from a 25-year period from 1975 to 2000. Matching Euro-Market interest rates are used to estimate the risk-free rate. The convenience yield approximation is both statistically and economically important in explaining variation between the futures price and the spot price after adjustment for interest rates. © 2002 Wiley Periodicals, Inc. Jrl Fut Mark 22:1005–1017, 2002

The author acknowledges LME for access to its price and inventory information and ARC for research funding (grant reference FRGS S62 040 10). Appreciation is also extended to the reviewers and particularly to the editor, Robert I. Webb, for their comments and suggestions.
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Received June 2001; Accepted February 2002

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The Journal of Futures Markets, Vol. 22, No. 10, 1005–1017 (2002)

Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/fut.10036

1. INTRODUCTION

Futures prices are generally explained in terms of the theory of storage as described in Kaldor (1939), Brennan (1958), Weymar (1966), and Working (1949) and further refined with the application of option-pricing theory (Heinkel, Howe & Hughes, 1990; Litzenberger & Rabinowitz, 1995; Milonas &Thomadakis, 1997a, 1997b).[1] It is argued that futures prices are determined by the cost of carrying the underlying asset. The simple cost of carry model includes the price of the underlying asset, interest rates, and physical storage cost. For commodities it is necessary to extend the simple model to include the impact of convenience yields to reflect benefits unique to holding the physical commodity. In finance theory the convenience yield is often modeled as a mean-reverting process with constant variance (Gibson & Schwartz, 1990; Schwartz, 1997), but this assumption constrains the convenience yield process. Doubtless, one reason for this simplifying assumption is the difficulty of approximating the convenience yield.

The approach taken in this article adopts a trading strategy similar to the selling opportunity available to the inventory holder in the two period models of Heinkel, Howe, and Hughes (1990) and Milonas and Thomadakis (1997a, 1997b). In both articles the producer chooses between buying the commodity and storing it or taking out a long futures contract with delivery of the commodity at the end of the second period. In these models, the commodity buyer has the option to sell the inventory at the end of the first period if the spot price is high enough. A similar argument is found in the two-period model of Litzenberger and Rabinowitz (1995), although the convenience yield is represented by marginal extraction costs. Application of these models to value the impact of the convenience yield generally requires specific information that is not available to the researcher.

The trading strategy driving the convenience yield approximation requires a change to the standard futures contract arbitrage on the basis of the pricing model. In the standard arbitrage model, traders are assumed to buy and hold the spot asset and short a futures contract if the futures price is greater than the cost of carry price. However, if the futures price is less than the cost of carry price, the arbitrager takes a long futures contract and shorts the spot asset. It is assumed that these

[1]Futures/forward price differences are ignored for simplicity of analysis. There may be marking to market effects, but the impact of marking to market is not included as a result of the perception that these effects are likely to be economically small (Benninga & Protopapadakis, 1994; Cornell & Reinganum, 1981; French, 1983; Pindyck, 1993).

positions are held until futures contract maturity. In developing an approximation for the convenience yield, traders are no longer required to hold the asset or the futures position until futures contract maturity. They may sell or buy opportunistically, similar to the strategies relied upon in the simple discrete models described previously. If it is known that prices will rise and then fall prior to maturity, then the holder of a long position (futures or spot) will prefer to sell at the maximum price, invest the proceeds at the risk-free rate, and then buy back again at the lower price at the futures contract maturity date.[2] Similarly, if it is known that the price will fall and then rise, then the short position holder will choose to borrow at the risk-free rate, buy at the low price, and sell at the futures maturity date when prices have risen again. To maximize the profit available under these strategies the trader requires perfect foresight. Although perfect foresight is unlikely, this strategy provides an approximation of the profits attainable from selective trading identified in the convenience yield literature, essentially imposing an upper limit on the convenience yield estimate.

The principal contribution of this article is the derivation of a simple approximation for the value of the convenience yield using a model advanced by Longstaff (1995) with three of the following input variables: the spot-price volatility, the futures price volatility, and the time to futures contract maturity. This article focuses on the impact of convenience yield on the futures prices of the nonferrous metals, copper, lead, and zinc. The simple cost of carry model is described in the next section, and this model is extended to include the impact of convenience yields. Data are described in Section 3; analysis follows in Section 4 with conclusions reported in Section 5.

2. FUTURES PRICING

The simple cost of carry model describes an arbitrage relation among the futures price, spot price, and the cost of carrying the asset. This can be written as

$$F_{itT} = S_{it}\exp(r_{tT} + w_{tT}) \tag{1}$$

where F_{itT} is the futures price for asset i, observed at time t, maturing at time T; S_{it} is the spot price observed at time t, for asset i; $\exp(\cdot)$ refers to

[2]This article ignores the further profits available to a monopolist in the final goods market who faces the market-demand schedule. It also ignores the possibility of multiple trades in particularly volatile periods.

the exponential function; r_{tT} is the continuously compounding risk-free rate of return applying to the period from t to T; and w_{tT} is the continuously compounding storage cost per dollar of spot price from time t to time T.

The difficulty with many applications of the simple cost of carry model is that this form of the model ignores the impact of convenience yield resulting in incorrect pricing of the futures contract. Although used in another context, a model described by Longstaff (1995) proves useful for approximating the value of a trading strategy open to a trader who holds a position in the spot asset and/or a futures contract.[3] Longstaff's (1995) model is briefly reviewed here in the context of buying and holding the spot asset, although the strategy could be applied to both long and short positions and to both the spot asset and the futures contract.

It is assumed that both the spot and futures price follow a Weiner process and that the horizon for the strategy is the futures contract maturity date (time T) when the spot-asset price is S_{iT}. The trader who chooses to store the commodity is assumed to know when the commodity price reaches a maximum over the period from now (time t) to the end of the analysis period (time T). The trader is assumed to exhibit perfect timing and price forecasting; therefore, this model should be viewed as providing a maximum value for the trading strategy.

Take the example of a time t commodity buyer. The buyer may choose to sell the commodity prior to futures contract maturity; thus, if a commodity sale does occur, the sale is timed to occur at the maximum price, S_τ, observed at time τ ($t < \tau < T$). The revenue from sale of the commodity at time τ is then invested at the risk-free rate until the end of the analysis period (time T) when the commodity is replaced at the market price. The maximum price over the period from time t to time T compounded to futures contract maturity is defined equal to

$$M_{iT} = \max_{0 \leq \tau \leq T} \{\exp[r(T - \tau)]S_{i\tau}\} \tag{2}$$

The value to a trader of buying the commodity and storing it is approximated by the value of the option to sell if the price rises sufficiently to generate a profit after buying back at time T. The value of this trading strategy is equal to

$$TS(S_{it}, T) = \exp[-r(T - t)]E(M_{iT}) - \exp[-r(T - t)]E(S_{iT}) \tag{3}$$

[3]Longstaff (1995) uses his model to identify upper bounds for the cost of marketability where a trader may be unable to trade because of an illiquid market. A "price discount," reflecting the cost of restricted marketability, is identified and used to highlight the possible financial impact of restricted marketability.

Longstaff (1995) provides a solution to this problem

$$TS(S_{it}, T) = S_{it}\left\{\left[2 + \frac{\sigma^2(T-t)}{2}\right]N\left[\frac{\sqrt{\sigma^2(T-t)}}{2}\right] + \sqrt{\frac{\sigma^2(T-t)}{2\pi}}\exp\left[-\frac{\sigma^2(T-t)}{8}\right] - 1\right\} \tag{4}$$

where $N(\cdot)$ is the cumulative normal distribution. Dividing by S_{it}, adding one to both sides, and taking natural logs gives the continuously compounding convenience yield estimate

$$\begin{aligned} ts_{tT}(S_{it}, T) &= \ln\left[1 + \frac{TS(S_{it}, T)}{S_{it}}\right] \\ &= \ln\left\{\left[2 + \frac{\sigma^2(T-t)}{2}\right]N\left[\frac{\sqrt{\sigma^2(T-t)}}{2}\right] + \sqrt{\frac{\sigma^2(T-t)}{2\pi}}\exp\left[-\frac{\sigma^2(T-t)}{8}\right]\right\} \end{aligned} \tag{5}$$

The trading opportunity available to the commodity buyer is also available to the futures contract buyer. The commodity short seller and futures contract seller would take opposite positions where the price falls and then rises. The value of profitable trading opportunities available to the underlying asset position relative to the value of profitable trading opportunities available to the futures contract position generates the approximation for the convenience yield (c_{tT}) used as

$$c_{tT} = ts_{tT}(S_{it}, T) - ts_{tT}(F_{itT}, T) \tag{6}$$

It is now possible to extend the futures pricing model in Equation 1 to include the convenience yield approximation giving

$$F_{itT} = S_{it}\exp(r_{tT} + w_{tT} - c_{tT}) \tag{7}$$

Taking logs and rearranging gives

$$\ln(F_{itT}) = \ln(S_{it}) + r_{tT} + w - c_{tT}$$

and

$$\ln\left(\frac{F_{itT}}{S_{it}}\right) - r_{tT} = w - c_{tT} = \mathrm{iab}_{tT} \tag{8}$$

The interest-adjusted basis (iab_{tT}) is a function of the storage cost and the convenience yield proxy, itself a nonlinear function of spot and futures price volatility and time to futures contract maturity.

3. DATA

The sample consists of quarterly observations from March 1975 to September 2000. The use of quarterly observations of 3-month futures contracts ensures that the data set spans a reasonably long period of time. It also avoids the problem of overlapping observations. Euro-interest rates and London Metals Exchange (LME) copper, lead, and zinc prices are collected for analysis. The copper and lead prices are denominated in Great Britain pounds, and the zinc price is denominated in U.S. dollars (USD). The Euro-currency (London) sterling 3-month midrate and the Euro-currency (London) USD 3-month mid-rate, obtained from Datastream, are used as estimates of the risk-free rate. The spot price and 3-month futures contract price are based on the official LME prices determined after the midday trading session on the last trading day in the quarter.[4] Prices are obtained from the Metal Bulletin over the period from March 1975 to December 1988 and from the LME web site for the period from January 1989 to September 2000.[5] Although there is some variation among the copper and zinc contracts in terms of the spot-asset definition (Sephton & Cochrane, 1991), the lead contract is essentially unchanged over the study period. All three commodities have traded consistently since 1975. For the commodities—copper and zinc—the price reflects an average price taken across the various categories reported in the LME. This is not necessary for the lead contract where only one price series is quoted at any time during the study period.

Quoted futures prices are for contracts with 3 months to maturity; therefore, in this article the futures contract time to maturity is assumed to be one quarter of a year. Spot-return variance and futures return variance are estimated using daily returns for the 20-trading-day period immediately preceding the end of the quarter when the spot price, futures price, and interest rate are observed.

Descriptive statistics are reported in Table I. Panel A includes the mean, standard deviation, maximum, and minimum, whereas Panel B

[4]LME prices are quoted as a representative range. The price used in the analysis is the midpoint of the range.

[5]Three standard deviation filters and graphical analyses are used to identify unusual observations, and these are compared with the original Metal Bulletin prices and corrected where necessary. All prices obtained from the site, http://www.lme.co.uk/, are quoted in USDs, and the GBP prices are calculated for copper and lead using the exchange rates accompanying the prices.

TABLE I
Descriptive Statistics and Time Series Statistics

Variable	*Mean*	*Standard Deviation*	*Minimum*	*Maximum*
Panel A: Descriptive Statistics[a]				
Convenience yield estimate (c_{tT})				
Copper	0.010	0.014	−0.022	0.084
Lead	0.016	0.024	−0.060	0.128
Zinc	0.013	0.018	−0.020	0.097
Interest-adjusted basis (iab_{tT})				
Copper	−0.017	0.028	−0.152	0.015
Lead	−0.013	0.031	−0.120	0.029
Zinc	−0.010	0.028	−0.096	0.055

Variables	$\rho(1)$	*PP(12)*	*Variable* $X^2(12)$	*Variable Squared* $X^2(12)$
Panel B: Time Series Statistics[b]				
Convenience yield estimate (c_{tT})				
Copper	0.21*	−9.87*	61.84*	12.29
Lead	0.17	−9.33*	24.20*	5.45
Zinc	0.46*	−7.08*	85.56*	37.65*
Interest-adjusted basis (iab_{tT})				
Copper	0.69*	−4.78*	185.78*	59.13*
Lead	0.56*	−5.91*	84.01*	28.39*
Zinc	0.56*	−5.70*	89.04*	45.79

[a]Descriptive statistics for the commodities copper, lead, and zinc include the mean, standard deviation, maximum, and minimum. Convenience yield estimate is the convenience yield approximation (see Equation 6). Interest-adjusted basis is the natural log of the futures/spot ratio minus the continuously compounding interest rate for the 3-month period. The data consist of 103 quarterly observations from March 1975 through to September 2000.
[b]Time series statistics for the commodities copper, lead, and zinc include the first-order serial correlation [$\rho(1)$], Phillips–Perron test for unit root [PP(12)], chi-square test for serial correlation in returns over 12 lags [$X^2(12)$], and chi-square test for serial correlation in squared returns over 12 lags [$X^2(12)$]. The data consist of 103 quarterly observations from March 1975 through to September 2000.
*Significant at the 5% level of significance.

contains time series information for the variables, including the first-order serial correlation coefficient, the Phillips–Perron statistic, and tests for serial correlation in the variable and squared variable. The Phillips–Perron tests suggest that the variables are stationary, although there is clear evidence of serial correlation in the variables. There is also some evidence of time-changing variance in the individual series consistent with the squared variable serial correlation results in Panel B. The average interest-adjusted basis for copper, lead, and zinc are −0.017, −0.013, and −0.010, respectively. The existence of negative values highlights the importance of the impact of the convenience yield in futures contract pricing over the period. The average convenience yield estimates for copper, lead, and zinc are 0.010, 0.016, and 0.013, respectively. These are reasonably close to the absolute value of the interest-adjusted basis.

4. ANALYSIS

As indicated in Equation 8 the interest-adjusted basis is a log-linear function of the convenience yield estimate and a constant. The constant provides an estimate of the average storage cost over the period expressed as a proportion of the spot price. Equation 8 also indicates that the interest-adjusted basis should decrease one for one with increases in the convenience yield. The regression equation used to test these characteristics is written as follows

$$\mathrm{iab}_{tT} = a_0 + a_1 c_{tT} + \varepsilon_t \tag{9}$$

where ε_t is the regression residual, and a_0, a_1 is the regression coefficients.

Initially, ordinary least squares regression was undertaken, although the regression residuals exhibited first-order serial correlation.[6] This serial correlation could be modeled using either an AR(1) process or a more general model including both current and lagged independent and dependent variables. A common factor restriction must hold if the AR(1) process is to be chosen in lieu of the more general model (Johnston & Di Nardo, 1997); thus, the restriction is tested using a Wald test. The common factor restriction could not be rejected in any of the regressions, and an AR(1) model is used for analysis with the results reported in Table II.

The intercept coefficient ranges from 0.1 to −1.0%, although this is never statistically significantly different from zero. The slope coefficients vary from −0.591 to −0.792, being statistically different from zero in all three cases. The slope coefficients are significantly different from negative one for copper and lead but not for zinc. This variation is not unexpected as the convenience yield variable used in the regressions is an approximation.

The chi-square tests and the Durbin–Watson statistic provide little indication of residual serial correlation in the AR(1) model. The same applies for time-changing variance in the regression residuals except for

[6]As a result of the use of quarterly observations, evidence of serial correlation is not the result of the overlapping observations problem.

TABLE II

Cochrane–Orcutt AR(1) Regression of Interest-Adjusted Basis on Estimated Convenience Yield

	Copper	*Lead*	*Zinc*
Constant	−0.010	−0.003	0.001
	(−1.88)	(−0.58)	(0.18)
c_{tT}	−0.708	−0.591	−0.792
	(−5.67*)	(−7.23*)	(−6.31*)
AR(1) coefficient	0.669	0.556	0.392
	(8.75*)	(6.64*)	(4.16*)
R-square	0.61	0.56	0.50
F-statistic	77.49*	62.92*	49.98*
Durbin–Watson statistic	2.24	2.01	1.93
Residual chi-square(12)	11.15	7.33	6.49
Residual squared chi-square(12)	8.49	7.25	19.93*
ARCH(1) test	2.00	1.67	6.87*
White's heteroskedasticity test	5.25	0.47	19.86*
Chow breakpoint test–LLR test	21.44*	2.51	12.86*

*Significant at the 5% level of significance. The data consist of 103 quarterly observations from March 1975 through to September 2000. A more comprehensive model was initially estimated consisting of contemporaneous and lagged variables. Wald tests were conducted for the common factor restriction implicit in an AR(1) model. The Wald tests failed to reject the null of an AR(1) process [chi-square statistic (1) = 0.002 with probability of 0.961 for copper, chi-square statistic (1) = 0.061 with probability of 0.805 for lead, and chi-square statistic (1) = 3.111 with probability of 0.078 for zinc]. The AR(1) models were then estimated using

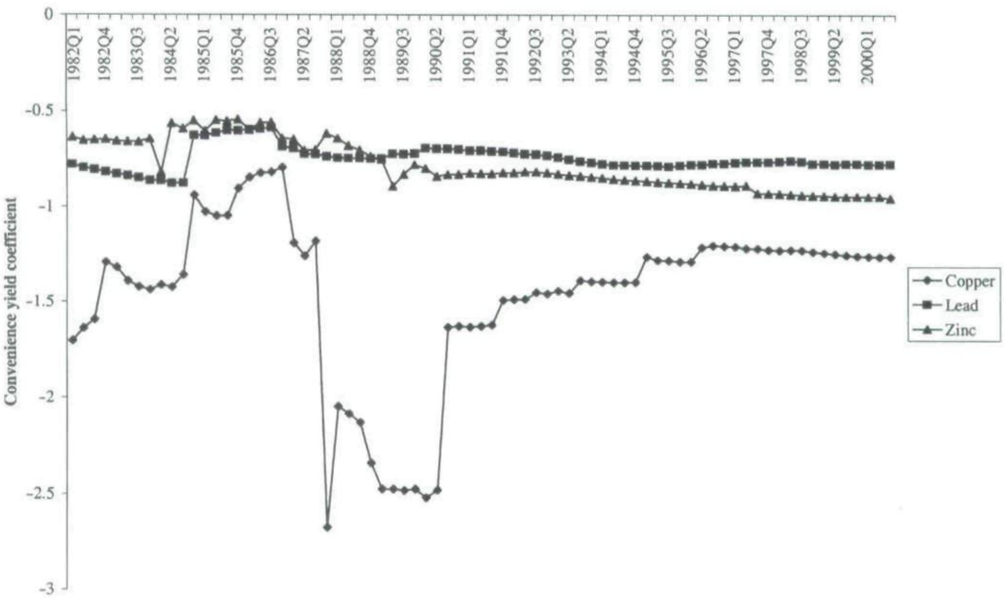
$$\mathrm{iab}_{tT} = a_0 + a_1 c_{tT} + \varepsilon_t \quad \text{with} \quad \varepsilon_t = \mathrm{RHO}\,\varepsilon_{t-1} + \eta_t$$

where $\mathrm{iab}_{tT} = \ln(F_{itT}/S_{it}) - r_{tT}$ = interest-adjusted basis, c_{tT} = convenience yield estimate, ε_t, η_t = residual term, and a_0, a_1 = regression coefficients. Coef is the estimated coefficient and *t* stat is the estimated *t* statistic.

The Durbin–Watson statistic and the residual chi-square(12) statistic provide tests of serial correlation in the regression residuals. The residual squared chi-square(12) statistic provides a test for ARCH in the residuals. There is little evidence of statistically significant serial correlation, but there is evidence of ARCH in the zinc residuals given chi-square tests on the basis of 12 lags. The ARCH(1) test and White's test for heteroskedasticity are also provided to test for nonconstant variance. The Chow test provides a test for structural change. The data are split (52/51), and a likelihood ratio-based Chow test is conducted to test for a change in the coefficients across the two subperiods. There is evidence of structural change in both the copper contract and the zinc contract with the slope coefficients closer to the predicted value of the negative one in the second subsample (from −2.234 to −0.600 for copper and from −0.422 to −1.118 for zinc). There is no evidence of structural change for the lead contract.

zinc. In the case of zinc an ARCH(1) model was fitted to the zinc data to adjust for this heteroscedasticity with little change in the parameter estimates. There is also some evidence of structural change over the period for copper and zinc. On analysis of the regression residuals for these commodities the structural-change test results are sensitive to a small number of observations.[7] When these observations are excluded from the regressions, the Chow test statistics for structural change are no

[7]One observation, 4th quarter of 1987, is excluded for copper, and seven observations are excluded for zinc—4th quarter 1984 through to the 2nd quarter 1985, the 2nd quarter 1986, the 2nd quarter 1990, the 4th quarter 1991, and the 3rd quarter 1997.



Source: Estimates of the convenience yield coefficients are obtained from recursive OLS regression estimation, starting with the first 25 observations and then re-estimating the coefficient as the time series data points are sequentially added to the dataset through to the most recent observation, September 2000.

FIGURE 1
Recursive OLS regression coefficient estimates for copper, lead, and zinc.

longer statistically significant, but exclusion of these observations has little impact on either the magnitude or statistical significance of the parameter values. There is also evidence that the coefficients for copper and zinc move toward the predicted value of negative one with increases in the sample size (Fig. 1). The recursive coefficient estimates for copper exhibit greater variation than those for either lead or zinc, particularly from the mid-1980s through the early 1990s. It is difficult to identify precise reasons for the greater volatility in the copper coefficient in the late 1980s and early 1990s, but it is possible that the positions held by Sumitomo may have had an adverse impact on copper pricing during this period (Gilbert, 1997).

The economic importance of the convenience yield adjustment can be better gauged from a comparison of the observed futures price and the theoretical futures price where the theoretical futures price takes two forms. The first is the simple cost of carry model, and the second is Equation 7 that includes the convenience yield approximation. The mean and standard deviation of the price difference and percentage price difference between the observed futures price and the theoretical futures

TABLE III
Analysis of the Impact of the Estimated Convenience Yield on Futures Price

	Copper	*Lead*	*Zinc*
	Futures Price Difference		
Simple cost of carry			
Mean	−18.448	−6.070	−12.156
Standard deviation	43.433	13.264	32.511
Cost of carry adjusted for convenience yield			
Mean	2.987	−0.481	−1.899
Standard deviation	33.487	10.427	21.275
	Percentage of Futures Price Difference		
Simple cost of carry			
Mean	−0.012	−0.014	−0.010
Standard deviation	0.030	0.032	0.028
Cost of carry adjusted for convenience yield			
Mean	0.006	0.001	−0.000
Standard deviation	0.025	0.026	0.022

Note. Mean and standard deviation of the dollar and percentage (with respect to the futures price) difference between the actual futures price and the theoretical futures price. The theoretical futures price is based on the simple cost of carry model both with and without adjustment for convenience yield effects. The convenience yield adjustment is based on the coefficient estimates reported in Table II for fixed storage costs (intercept) and convenience yield value weighting (slope) as per Equation 9.

price are reported in Table III for copper, lead, and zinc, respectively. The convenience yield adjusted cost of carry price is based on Equations 7 and 9 giving

$$F_{itT} = S_{it} \exp(r_{tT} + a_0 + a_1 c_{tT}) \tag{10}$$

The price obtained from the simple, or unadjusted, cost of carry model (Equation 1, with $w = 0$) is higher than the observed futures price on average. The inclusion of the estimated convenience yield results in a substantial reduction in the pricing difference. For copper, the average percentage pricing error falls from −1.2 to 0.6%, whereas for lead and zinc the average percentage pricing error falls from −1.4 to 0.1% and from −1.0 to −0.0%, respectively. The variance in the difference and percentage difference also reduces after adjustment for convenience yield impacts.

5. CONCLUSION

This article suggested an approximation for the impact of convenience yields on commodity futures prices. The convenience yield estimates for copper, lead, and zinc were both statistically and economically important in explaining futures pricing over the period from 1975 to 2000 for these commodities. The results are consistent with the existence of the convenience yield effect described in Heinkel, Howe, and Hughes (1990) and Milonas and Thomadakis (1997a, 1997b). The model used to value the convenience yield (Longstaff, 1995) assumes that a profit-maximizing trader has perfect foresight. A trader holding a long position will sell at the maximum price and buy at maturity where it is known that the price will increase and then fall prior to futures contract maturity. Where a short position is held, the trader will buy at the minimum price and sell at maturity where it is known that the price will fall and then rise prior to futures contract maturity. The convenience yield estimates based on these trading strategies explain much of the simple "cost of carry model" pricing error both in terms of statistical significance and economic importance.

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